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FLOW SCIENCE®

FINAL REPORT

In-Delta Storage Program
State Feasibility Study
Reservoir Stratification Study

by

Flow Science Incorporated

Prepared
for

The Department of Water Resources
Task Order Number IDS-0303-1841-016

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FSI 034022
July 23, 2003

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SUMMARY

The Department of Water Resources is conducting a feasibility-level study of the In-Delta Storage Program in the Sacramento-San Joaquin Delta under CALFED's Integrated Storage Investigations Program. The focus of the In-Delta Storage Program is the Re-engineered Delta Wetlands Project. As part of the project evaluations, the Department is evaluating the technical feasibility of developing storage on Webb Tract and Bacon Island, with Bouldin Island and Holland Tract used for mitigation.

Flow Science Incorporated, under subcontract to CH_2M HILL, Inc., has conducted a modeling study to determine if the reservoir islands (Webb Tract and Bacon Island) will stratify and to predict temperature differences between the islands and adjacent channels for different operational scenarios of the In-Delta Storage Project.

Simulations of reservoir temperature were conducted for three years: 1979, 1986, and 1987. These years were selected in consultation with DWR to represent conditions within the reservoirs during a range of hydrologic and reservoir operation conditions. The selected years were representative of "average," wet, and dry conditions.

Wind speed, solar insolation, reservoir depth, reservoir inflows and outflows, and other factors can lead to stratification within reservoirs. The simulation results presented here demonstrate that the development of stratification within the reservoirs and the modeled temperature of water within the reservoirs is highly sensitive to wind speed, as would be expected with a shallow reservoir. Because wind speed measurements were not available at the exact locations of the proposed reservoirs, a range of wind speeds were evaluated, based upon measurements at other Delta locations. For certain simulation periods (e.g., 1979, 1986), the lowest modeled wind speeds led to simulated stratification during the summer time period. The higher wind speed scenarios led to short-lived periods of minor stratification for all modeled years.

Because of the limited scope of work conducted for this study, the results presented here are not intended to support conclusions beyond the scope of this report. Additional study could be undertaken to address issues related to the conclusions presented in this report. For example, weather stations installed at the proposed reservoir locations could be used to measure wind speeds at the actual reservoir locations and to refine model results. Sensitivity analyses could be undertaken to address the impacts of other model parameters (in addition to wind speed) on the development of stratification and simulated temperature within the proposed reservoirs. Nevertheless, it is evident that the range of wind speeds employed in this analysis are very likely to capture the expected range of reservoir behavior. Impacts on ecological systems and biogeochemical processes were beyond the scope of this study, as were evaluations of impacts of short-term (e.g., diel) stratification.

INTRODUCTION

The study modeled three representative years from the longer simulation of the CALSIM II/DSM2 modeled record. The years were selected by DWR to represent a broad spectrum of operational conditions, with 1979 representing operations under "typical" conditions, 1986 representing wet conditions, and 1987 simulating operations under dry conditions.

MODEL OVERVIEW

There are many complex physical, chemical, and biological interactions within a reservoir. To help understand these interactions and better manage a reservoir, simulation models can be used. Experiments and field measurements have long shown that the horizontal temperature variation in reservoirs is almost non-existent. This fact allows a reservoir to be efficiently modeled in a one-dimensional fashion (in the vertical direction). By considering the appropriate physical processes and including a biochemical model, water quality in lakes and reservoirs can be accurately predicted. The computer program, DYRESM-WQ (Dynamic Reservoir Model - Water Quality), is a one-dimensional model that predicts temperature, salinity and water quality in a reservoir by integrating a process-based physical model with a biochemical model. It is owned by the Center for Water Research at the University of Western Australia. Flow Science is exclusively responsible for the development, application, and distribution of DYRESM-WQ in North America. DYRESM-WQ has been used in predicting water quality in many lakes and reservoirs throughout the world. In the U.S. it has recently been applied to San Vicente Reservoir (City of San Diego), Los Vaqueros Reservoir (Contra Costa Water District), and Lake Youngs (Seattle Water Department). The comprehensive inclusion of physical processes and water quality variables makes DYRESM-WQ a powerful management tool for predicting reservoir mixing and water quality issues.

DYRESM-WQ Physical Processes

Based on the aforementioned one-dimensionality assumption, a reservoir is divided (for modeling purposes) into a series of horizontal slabs or layers (typically 30 to 100 elements). Due to either inflow or rainfall, some layers may in the course of a simulation become too thick and are thus split in order to provide the desired resolution. Conversely, layers that become too thin (due to outflows or evaporation) are combined with their neighbors. The physical processes modeled also impact the time step taken in the model. Surface heat and momentum flux limitations cause the modeling time step to decrease automatically in periods of rapid change. With checks on resolution in both space and time, DYRESM-WQ is computationally efficient.

DYRESM-WQ includes surface heat, mass, and momentum exchange, surface mixed-layer deepening, inflows and outflows, and mixing in the hypolimnion. Sensible, evaporative, and radiative heat transfer are accounted for in determining the change in temperature of the top layers of the reservoir. The heating/cooling of the surface layer affects the deepening of this layer via convective mixing. In addition, stirring by the wind and the resulting internal fluid shear production and billowing contribute to the mixing of the surface layer and are all included in the program algorithms.

The one-dimensionality assumption used in DYRESM modeling is based on the density stratification usually found in lakes and reservoirs. This stratification inhibits vertical motion, while lateral and longitudinal variations in density are quickly relaxed by horizontal convection, which typically occurs on time scales faster than vertical advection. Horizontal exchanges generated by weak temperature gradients communicate over distances of several kilometers on time scales of less than a day, suggesting that a one-dimensional model is suitable for simulations over daily time scales. In any case, the vertical mixing resulting from such short time scale motions is to some extent encapsulated in the vertical diffusion incorporated into the modeling.

DYRESM-WQ is capable of handling both surface and submerged inflows. Based on its density, the inflow travels up or down in the reservoir, entraining reservoir water along the way. Throughout this process, water properties (temperature, salinity, water quality) are updated as the water mixes with the entrained water. This continues until the inflow reaches its level of neutral buoyancy, upon which it is inserted into the appropriate layer. Water withdrawal also influences the reservoir layer structure. When water is taken from a submerged intake in a stratified reservoir, most water is withdrawn from a thin layer centered about the intake. DYRESM-WQ determines the thickness of this layer based on the stratification and the type of intake (line or point sink).

Mixing of water in the hypolimnion is treated as a diffusive process, with an eddy diffusivity dependent on the rate of dissipation of turbulent kinetic energy within the reservoir. DYRESM-WQ optionally allows the user to model air bubble plume destratification systems with fine bubbles. These systems are modeled as buoyant plumes within the reservoir.

Water quality parameters can also be modeled using DYRESM. These parameters are treated in a similar manner to the physical water properties (temperature and salinity) when considering the effects of the mixing processes. When the layers are adjusted, new concentrations of the water quality parameters are calculated based upon volumetric averages of the pertinent layers. The water quality model in DYRESM-WQ accounts for dissolved oxygen (DO), algae, nutrients, zooplankton, metals, and pH. Water quality modeling was not conducted for this project, and the results presented here are not intended to support conclusions beyond the scope of this report. Short-term effects (e.g., effects related to diel stratification) and impacts on biogeochemical and ecological processes are beyond the scope of this evaluation.

INPUT DATA

The DYRESM model requires the following input information:

- meteorological data
- lake morphometry data
- inflow data
- outflow data
- physical data
- initial profile data

These parameters and the values used in the modeling are described briefly below.

Meteorological Sensitivity Analyses

The meteorological data required to run the model include daily values of short wave and longwave radiation, air temperature, vapor pressure, wind speed and rainfall. For this study, three data collection locations were identified. Meteorological data have been collected at Twitchell Island, located 3.3 miles from Webb Tract and 12 miles from Bacon Island, from 1997 to present. The database for Brentwood, located 10 miles from Webb Tract and 7 miles from Bacon Island, extends from 1985 to present. Historical meteorological records used for the 1979 simulation were obtained from the Solar and Meteorological Surface Observation Network 1961-1990.[1] The closest site to the Delta in the NCDC database is Sacramento, which is located 31 miles from Webb Tract and 33 miles from Bacon Island. Figure 2 shows the location of the three meteorological data collection stations used in the analysis.

In order to provide appropriate weather data at the reservoir locations for the targeted years (1979, 1986, and 1987), two statistical analyses were performed. Because none of the observation stations is located precisely at the locations of the proposed reservoirs, an analysis was conducted to investigate the range of meteorological data values that occur near the reservoir locations in the Delta. This analysis was used to select the data values used in the DYRESM modeling. These data extrapolations were necessary to simulate conditions for the three years modeled in this study (1979, 1986, and 1987). Despite the lack of measured data, DWR selected these years for the model simulations as representative of the range of hydrologic and operating conditions likely to be experienced by the reservoirs. While the input data used in these simulations are believed to be representative of the range of conditions experienced at these reservoirs for the modeled years, these data may not represent the full range of meteorological conditions that may occur at the reservoir locations over an extended time period (see discussion in Conclusions and Recommendations). Nevertheless, they will certainly capture most of the generally expected range of conditions. It may be possible that an extended period without wind and with high solar flux could occur at the site, but it is quite unlikely.

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[1] U.S. Department of Commerce, National Climatic Data Center, Volume III Western U.S. Version 1.0, September 1993, "Solar and Meteorological Surface Observation Network 1961-1990."

The first analysis compared data collected at Twitchell Island to data collected at Brentwood for the overlapping record period of 1998-2002. Results demonstrate that the rainfall and radiation data were not statistically different between these two locations. Meteorological sensitivity plots are contained in Appendix A. A comparison of precipitation and solar radiation data records is shown on page A-1. The analysis also indicates significant variation in the mean values of the wind speed, vapor pressure, and temperature between the two locations. To determine the magnitude of variation for these parameters, data were blocked by month and analysis of variance (ANOVA) testing was conducted on the mean monthly values for the two sites.

Twitchell Island was used as the baseline (due to proximity to Webb Tract) and Brentwood data were found to vary from Twitchell data by the following percentages:

Rainfall	0%
Solar Radiation	0%
Vapor Pressure	-4.0%
Temperature	-2.5%

After application of the above factors to each daily record over the five-year interval, a follow-up sensitivity analysis found no statistically significant difference between the weather data collected at Twitchell Island and the scaled data from the Brentwood site. Plots on pages A-2 through A-4 show the agreement between the adjusted meteorological data (Brentwood) and the baseline reference data (Twitchell) predicted by the statistical analysis. These scale factors were then applied to Brentwood records for 1986 and 1987 data sets, which were then used for both islands in the DYRESM simulations.

Because data nearer the proposed reservoirs were not available, the NCDC Sacramento data were used for the 1979 simulations. To use these data in the modeling, the scaled Brentwood data were used as the reference set and compared to overlapping Sacramento data (1986-1990). The five-year overlap interval was evaluated to examine the variation in the mean values between the scaled Brentwood data and the Sacramento data. The initial iteration determined statistically significant differences between the mean monthly values for all parameters. To optimize agreement between the data sets, Sacramento data used in the model were scaled as follows:

Rainfall	+75%
Solar Radiation	-1.0%
Vapor Pressure	-5.0%
Temperature	-3.0%

After application of the above factors to each daily record over the 5-year interval, a follow-up sensitivity analysis found no statistically significant difference between the scaled weather data collected at Brentwood and data scaled from the National Climatic Data Center (NCDC) data set for Sacramento. Pages A-3 and A-4 show a comparison of the scaled data to the baseline set for the interval analyzed. These scale factors were applied to NCDC weather data at the Sacramento site and then used in the 1979 DYRESM simulation for both reservoirs.

Wind Speed Scaling Approaches

The potential energy of a lake may change in two ways: first, wind stirring redistributes layers of different densities; second, the heat loss or gain can change the density distribution. Wind speeds are generally the most important of these processes, and wind speeds may vary significantly over the course of any given day. The DYRESM model recognizes this and makes an adjustment as it uses wind speed to calculate the energy applied to a reservoir. This adjustment was developed during DYRESM model development using empirical data from Wellington Reservoir, Western Australia. If more extreme variations in wind speed occur within the Delta over the course of a 24-hour period than were observed in the model calibration reservoir, the model will underestimate mixing (i.e., overestimate stratification) within Delta reservoirs. Because detailed wind data were not available for the Delta reservoir locations, no comparison was undertaken.

Because wind speeds are so important in simulating stratification within reservoirs, the accuracy of wind input to the model is a critical factor in predicting lake behavior. Two approaches were used to adjust the available wind records (collected at Twitchell Island, Brentwood, and Sacramento) for use in the DYRESM simulation.

Wind patterns and wind speeds can vary significantly from location to location, and selection of the most representative site cannot be based exclusively on proximity. Two alternative scaling methods were used in order to present an estimate of reservoir behavior in both maximum and minimum wind conditions. Brentwood is somewhat sheltered due to its proximity to the adjacent hills. Thus, Brentwood wind data were selected to represent a low wind condition at Webb Tract and Bacon Island. Twitchell Island, located in an open, low area, represents higher wind conditions in the Delta and was used to model higher windspeeds at both proposed reservoirs.

For the 1979 analysis, the low wind condition was established through a 5-year, multiple comparisons test between Brentwood and Sacramento. For the high wind condition, a two-tiered approach was used to first scale Brentwood wind data to Twitchell Island, followed by a multiple comparisons test to scale Sacramento data to represent high wind speed at Twitchell. A summary is presented in Table 1.

Table 1 Wind Scaling Approach for the 1979 Simulation

Duration Evaluated	Baseline Site	Adjusted Location	Scale Factor Applied	Wind Estimate	Year Simulated
1986-1990	Brentwood	Sacramento	-25%	Low	1979
1998-2002	Twitchell	Brentwood	+57%	High	1979
1986-1990	Brentwood +57%	Sacramento	+10%	High	1979

For the 1986 and 1987 simulations, recorded wind data were available at the Brentwood site and used directly in the model for the low wind scenario. When scaling Brentwood data to model high wind conditions (i.e., to approximate wind conditions as observed at Twitchell), different scaling factors were used for different wind speeds. As shown in Figure A-5, a uniform spatial scaling factor applied to all data resulted in poor agreement at high speeds. To account for this variation, an alternative approach to scaling the wind speeds was investigated.

For the five-year overlap interval, measured wind speeds at Brentwood were sorted according to the following four bins:

$$0\ {}^{m}\!/\!{}_{s} \le u_1 < 2\ {}^{m}\!/\!{}_{s}$$
$$2\ {}^{m}\!/\!{}_{s} \le u_2 < 4\ {}^{m}\!/\!{}_{s}$$
$$4\ {}^{m}\!/\!{}_{s} \le u_3 < 6\ {}^{m}\!/\!{}_{s}$$
$$6\ {}^{m}\!/\!{}_{s} \le u_4$$

A regression was then developed to determine the appropriate scaling relationship for each bin. Plots and equations for this approach are shown in Figure A-6. Additional scatter plots shown in Figure A-7 investigate the agreement for the two spatial scaling approaches. Preliminary model runs using both wind scaling approaches were conducted for the 1986 and 1987 simulations.

Lake Morphometry

The lake morphometry file consists of an array of reservoir volume and surface area at various heights above the bottom of the reservoir. Capacity curves for Webb Tract and Bacon Island are presented in Figures 3 and 4 respectively.[2] Numeric relationships are tabulated in Table 2 and Table 3.

[2] www.isi.water.ca.gov/ssi/indelta/docs/APPENDIX%20C% 20TABLES.pdf

Table 2 Stage Storage Volumes for the Proposed Storage Reservoir on Webb Tract

Elevation		Surface Area		Total Volume	
(m)	(ft)	(m^2x1000)	(acres)	(m^3x1000)	(acre-ft)
-6.7	-22	0	0	0	0
-6.1	-20	769	190	180	146
-5.5	-18	5257	1299	1517	1230
-4.9	-16	11894	2939	6029	4888
-4.3	-14	15245	3767	13672	11084
-3.7	-12	17422	4305	23360	18938
-3.0	-10	19583	4839	34337	27837
-2.4	-8	20627	5097	46184	37442
-1.8	-4	21497	5312	71460	57933
-0.6	-2	21562	5328	84477	68486
0	0	21622	5343	97630	79150
0.6	2	21687	5359	110871	89884
1.2	4	21748	5374	124168	100664

Table 3 Stage Storage Volumes for the Proposed Storage Reservoir on Bacon Island

Elevation		Surface Area		Total Volume	
(m)	(ft)	(m^2x1000)	(acres)	(m^3x1000)	(acre-ft)
-6.1	-20	0	0	0	0
-5.5	-18	623	154	107	87
-4.9	-16	4197	1037	1204	976
-4.3	-14	9118	2253	4972	4031
-3.7	-12	15119	3736	11845	9603
-3.0	-10	21452	5301	23075	18707
-2.4	-8	21631	5345	37431	30346
-1.8	-6	21703	5363	53780	43600
-1.2	-4	21772	5380	71029	57584
-0.6	-2	21845	5398	88620	71845
0	0	21914	5415	106240	86130
0.6	2	21987	5433	123999	100527
1.2	4	22055	5450	141808	114965

Additional requisite geometric parameters were obtained through GIS krieging of spot elevations.[3] Figures 5 and 6 show the resulting contours. These were used to determine the length and width of the basin at the centerline of each inlet and outlet structure.

[3] Recent survey spot elevations were provided by Ayres Associates.

Inflow

Inflow to a reservoir introduces kinetic and potential energy to the system. For example, the velocity of an inflow adds mixing energy to the reservoir. In addition, a temperature difference may exist between the inflow and the resident water, resulting in mixing due to buoyancy. The geometry and spatial position of the inflow conduits also affect the mixing characteristics of the system.

Integrated Resource Facilities

Inflow and outflow to each of the proposed reservoirs will be controlled by two integrated resource facilities at each reservoir location, shown in Figures 5 and 6 for Webb Tract and Bacon Island, respectively. Flow conveyance structures at the facilities consist of three gates and three pipes. As shown in Figure 7, inflow from the river to the inflow forebay is through gate 1. Diversion or discharge between the reservoir and the forebay is through gate 2. Discharge to the river from the forebay is through gate 3. In addition, three pipes at each Integrated Resource Facility (IRF) can be used to pump water into or out of the reservoirs. Two of the pipes are 8 feet in diameter and the third has a diameter of 6 feet. Flow through the gates is via gravity, while pumped flow is exclusively through the conduits. Table 4 shows the dimensions of gates and pipes for each integrated facility.

Table 4 Elevations of Structural Components for each Integrated Facility.

<table>
<tr><th>Structural Component</th><th>Item</th><th>Description</th><th>Webb Tract San Joaquin River</th><th>Webb Tract False River</th><th>Bacon Island Middle River</th><th>Bacon Island Santa Fe Cut</th></tr>
<tr><td rowspan="6">Gate Structures</td><td rowspan="2">Gate 1 (Inflow)</td><td>Sill Elevation</td><td>-12</td><td>-15</td><td>-13</td><td>-8</td></tr>
<tr><td>Dimensions</td><td colspan="4">See note (a).</td></tr>
<tr><td rowspan="2">Gate 2 (Transition)</td><td>Sill Elevation</td><td>-18</td><td>-18</td><td>-16</td><td>-16</td></tr>
<tr><td>Dimensions</td><td colspan="4">See note (a).</td></tr>
<tr><td rowspan="2">Gate 3 (Outflow)</td><td>Sill Elevation</td><td>-15</td><td>-16</td><td>-12</td><td>-8</td></tr>
<tr><td>Dimensions</td><td colspan="4">See note (a).</td></tr>
<tr><td rowspan="4">Conduits</td><td rowspan="2">Invert Elevations</td><td>Reservoir Side</td><td>-12</td><td>-12</td><td>-10</td><td>-10</td></tr>
<tr><td>Bypass Channel Side</td><td>-12</td><td>-12</td><td>-10</td><td>-10</td></tr>
<tr><td rowspan="2">Number of conduits</td><td>8-ft diameter</td><td>2</td><td>2</td><td>2</td><td>2</td></tr>
<tr><td>6-ft diameter</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
</table>

(a) Each gate structure contains three side-by-side culverts, each 12 feet wide by 10 feet high.

Surface Inflow

In DYRESM, each daily inflow is stacked into an element that contains the volume (Q), temperature (T), salinity (S), and depth (d). Each element flows at an initial depth determined from the Froude number and conservation of energy and momentum. As each stack moves, it entrains fluid from the reservoir. DYRESM models entrainment in two ways. Inflow is either a surface or a submerged condition.

For the surface inflow (e.g., via gates) as each element enters, it entrains fluid from the reservoir according to the following equation:

$$h = 1.2E\,dx + h_o$$

Where E is the entrainment coefficient, dx the distance traveled, and h_o the initial flowing depth, obtained from conservation of volume and momentum. The evaluation of h_o depends on the local Froude number of the flow (F_i).

Submerged Inflow

Submerged inflows (e.g., via pipes) are directed to travel up or down in the reservoir depending on the inflow's density relative to the local density of the reservoir. The submerged inflow is inserted at its level of neutral buoyancy. Entrainment of reservoir water affects the placement of this inflow. Entrainment is accounted for by calculating the volumetric flow rate at a location z above or below the submerged inlet centerline using the jet entrainment equation.[4]

Outflow

Daily outflow volumes in the CALSIM model are withdrawn from the central pool of the IRF. All outflows were simulated to enter the central pool via gravity flow through gate 2.

CALSIM Analyses

Daily inflow and outflow volumes were provided by the sixteen-year CALSIM analysis conducted by DWR. This report presents results based upon CALSIM runs provided by DWR on July 15, 2003. In order to accurately assess mixing characteristics of the integrated facilities, daily flow volumes were apportioned to the appropriate structure. This was accomplished by using the results of the operational CALSIM stage analysis conducted by DWR. The stage analysis optimized efficiency by using gravitational energy to the greatest extent possible. Gate curves were developed by DWR based on a range of head differentials between the reservoir and the adjacent channels.

River stage values were obtained from the model run provided by DWR on July 18, 2003. Reservoir water surface elevations were obtained from the DYRESM model using the appropriate geometric configurations and daily flow volumes from the CALSIM analysis. The

[4] Fischer, H., List, E.J., Koh, R.C., Imberger, J., and N.H. Brooks. 1979. Mixing in Inland and Coastal Waters. Academic Press.

difference between the DYRESM reservoir surface elevations and the CALSIM river stages[5] was then used in conjunction with the gate curves developed in the stage analysis to apportion the total inflow volume between gravitational inflow and pumped inflow. Figures 8-13 plot the resulting flow distribution for each facility for the years simulated. The gravitational component was modeled as a surface flow through gate 2 and the pumped component was modeled in DYRESM as conduit flow.

Physical Data

The primary physical parameters that govern stratification are salinity and temperature. The salinity of the simulated inflows was obtained from daily average EC measurements compiled by the Interagency Ecological Program. Table 5 shows the stations utilized and their proximity to each reservoir.

Table 5 Interagency Ecological Program Source for EC measurements

IEP Station Number	Reservoir	Distance	Model Year
RFAL008	Webb Tract	adjacent	1979
RSAN032	Webb Tract	0.8 miles	1986 and 1987
ROLD014	Bacon Island	0.9 miles	1979
RMID015	Bacon Island	adjacent	1986 and 1987

For DYRESM input files it was necessary to convert EC data to a corresponding total dissolved solids (TDS) value. Site-specific conversion equations were obtained from a 1986 Department of Water Resources study.[6] Figure 14 shows the location of the EC sampling sites and the database location for the DWR site-specific conversion algorithm.

1979 Temperature Data

Historical river temperature data in the Delta are limited. The nearest station with 1979 data is USGS station 11303500, located on the San Joaquin River near Vernalis. This station is located 24 miles from Bacon Island and 33 miles from Webb Tract. To assess the validity of employing this data set, statistical sensitivity analyses were conducted using more recent

overlapping measurements for Middle River and the San Joaquin River monitoring stations. River temperature readings were blocked by month. Months where either data set lacked

[5] Stage values from the CALSIM Analysis at channel 45_0 were used for the North facility at Webb Tract (San Joaquin River); stage elevations from channel 276_0 were used for the South facility at Webb Tract (False River). For Bacon Island, the elevation at channel 153_0 was used for the North Facility (Middle River) and channel 258_4295 was used for the South facility (Santa Fe Cut).
[6] June 24, 1986, The Department of Water Resources, Salinity Unit Conversion Equations. Memorandum to Peter Lee from Kamyar Guivetchi. Site ID 24 “ROLD21”, the Old River 0.5 km S. of the North Tip of Palm Tract, was selected for Bacon Island, and site ID “31 LFKT3”, Franks Tract, Center of NW Quadrant, was selected for Webb Tract conversions.

readings were removed from the analysis; a total of 113 (1991-2001) months were compared in the spatial sensitivity test. Results indicate no significant difference between temperatures measured at the two locations so that no scale factor was applied, and temperature records from USGS Station 11303500 were used directly in this analysis. Daily average temperature measurements from the San Joaquin River near Vernalis and for Middle River are plotted in Figure 15.

1986 and 1987 Temperature Data

Historical hourly temperature values were recorded during 1986 and 1987 at the IEP Antioch site RSAN007, which is located approximately 3 miles from Webb Tract and 6 miles from Bacon Island (see Figure 15). These data were used for the 1986 and 1987 DYRESM simulations. A comparison of available temperature measurements (data provided by DWR) is shown in Figure 16. The locations of the stations where temperature measurements were available are shown in Figure 17. As shown in Figure 16, there is often little overlap in temperature measurements collected from various locations in the Delta. The data comparison, though limited, appears to support the use of temperature measurements from the Antioch station to represent the temperature in the channels adjacent to both Webb Tract and Bacon Island.

As an additional sensitivity evaluation, in-reservoir water temperatures were simulated for the 1986 model year using as model input measured temperature data from both the Antioch site and the USGS San Joaquin River site near Vernalis. Results showed little difference in simulated in-reservoir temperatures, again supporting the use of water temperature data from the Antioch site in the DYRESM simulations.

Initial Profile Data

The initial stages in each reservoir at the start of the simulation were set using CALSIM results for January first in 1979, 1986, and 1987. Initial stages used in the simulation are shown in Table 6. Appropriate water quality data from adjacent channel reaches were used to estimate in-reservoir initial water quality parameters.

Table 6 Initial Reservoir Stages for Simulations

Date	Stage Webb Tract	Stage Bacon Island
1/1/79	-5.19 feet	-1.7 feet
1/1/86	-8.3 feet	-1.85 feet
1/1/87	-1.50 feet	-0.22 feet

DYRESM RESULTS

Three primary criteria influence reservoir mixing and stratification. These are the mixing energy associated with inflow and outflow and the temperature and salinity gradients, which establish the region of insertion (or withdrawal) and resulting flow density.

1979 (Typical Year)

The year 1979 was selected by DWR as a typical year. All data pertaining to the 1979 simulation are plotted in Appendix B. Scaled Sacramento meteorological records, plotted on page B-1, were used for all 1979 simulations.

Webb Tract

Results of the CALSIM simulation indicate that Webb Tract Reservoir contains 16.8 feet of water at the beginning of the simulation (1/1/79). The operational scenario for this round of modeling employs a pulsed flow pattern as shown in the inflow and outflow plots on page B-2. A comparison of DYRESM results for the low wind scenario (plotted on page B-3) to the high wind profile (on page B-4) indicates that thermal stratification is more likely to occur at lower wind speeds, as expected. Stratification in this simulation is short-lived (a few days) and quite weak; this minor stratification tends to occur when wind speeds are on the order of 2 m/s. The Sacramento wind records scaled to approximate wind speeds at Brentwood (Figure B-3) represent a worst case, low wind speed condition. Hills located to the southwest of the reservoir sites likely cause a sheltering effect at Brentwood, as the general wind direction in the Delta is southwesterly. Use of higher wind speeds in the modeling (Sacramento wind records +57%) does not result in simulated stratification.

Predicted reservoir temperatures are influenced by wind speed, atmospheric temperature, solar radiation, and source water temperature. A comparison of the simulated reservoir temperature (high wind scenario) to the river channel temperature, both taken at the water surface, is plotted on page B-5. The high wind scenario reduces the overall temperature of water within Webb Reservoir. In general, measured surface water temperatures are slightly greater than simulated reservoir water temperatures. During the period of May through June 1979, only a few measured water temperature values are available, and it is difficult to form conclusions regarding the difference between the simulated temperature of water in the reservoirs and measured temperatures in the adjacent channel.

Simulated salinity concentrations in Webb Tract Reservoir are primarily influenced by the salinity of the inflow, which is a function of the conditions in the adjacent channels. The initial salinity of water in the reservoir is set at 120 mg/L, corresponding to the daily average salinity recorded in the San Joaquin River adjacent to Webb Tract on January 1, 1979. The pulsing inflow affects the simulated salinity concentrations at depth in the reservoir, particularly in the low wind scenario (Figure B-3), when "spikes" of elevated salinity at the base of Webb Reservoir result from inflows of higher salinity water from the adjacent channel. In the high wind scenario, mixing within the reservoir is more complete but the influence of the pulsed inflow can still be observed (Figure B-4). In late July through August inflow is zero and the outflow volume increases (Figure B-2). The simulated salinity of the reservoir increases in response to higher salinity of the inflow (Figure B-6) to result in salinity concentrations of approximately 300 mg/L in late September and November. In December, the salinity concentration in the San Joaquin River near Webb Tract decreases (Figure B-6), resulting in a reduction in the TDS concentration of Webb Reservoir to approximately 210 mg/L at the end of 1979 (Figure B-4).

Bacon Island

Results of the CALSIM analysis indicate that the Bacon Island Reservoir contains approximately 18.3 feet of water at the beginning of the simulation (1/1/79). The reservoir receives a large volume of inflow at the end of February (see Figure B-7). From the end of February through May and from September through the end of the year, inflow approximately equals outflow. These pulses of inflow and outflow are intended to improve circulation and water quality within the reservoirs (DWR, personal communication).

A comparison of the DYRESM temperature profiles for the low wind and high wind conditions, plotted in Figures B-8 and B-9, respectively, indicate that there is a potential for minor, short duration thermal stratification at lower wind speeds in mid-August through mid-September. In addition to influencing the reservoir's well mixed condition, higher wind speeds also lead to lower overall reservoir temperatures, as seen on Figure B-9.

Salinity in Bacon Reservoir is primarily influenced by the conditions in the adjacent channels. The initial concentration for the simulation is the same as the average daily value measured on January 1, 1979 in the Middle River adjacent to Bacon Island (approximately 130 mg/L). The simulated salinity of the water in Bacon Island Reservoir rises to a near constant value of just more than 200 mg/l through then end of July. The highest simulated salinity concentration in the reservoir (about 380 mg/L) occurs in October 1979, in response to inflows of high salinity water from the adjacent channel. The simulated salinity concentration of Bacon Reservoir was reduced to about 190 mg/L by the end of 1979. As with the 1979 Webb Tract reservoir simulation, "spikes" of salinity are simulated to occur in the base of Bacon Reservoir (see Figure B-8).

1986 (Wet Year)

The year 1986 was selected by DWR to represent reservoir conditions during a wet year. All plots pertaining to the 1986 simulation are presented in Appendix C. Wind data records resulting from the three approaches are plotted on page C-1.

Webb Tract

Results of the CALSIM simulation indicate that Webb Reservoir contains 13.7 feet of water at the beginning of the simulation (1/1/86). Daily inflow and outflow volumes are shown in Figure C-2. DYRESM reservoir profiles are plotted on pages C-3 through C-5 for each of the wind scenarios evaluated in the 1986 simulation. As shown in these figures, all scenarios predict some stratification. Stratification is most pronounced, and reservoir water temperatures are highest, for the low wind speed simulation assumptions (Figure C-3). For all wind speed scenarios, the potential for stratification is reduced in August, and stratification is eliminated in September. The potential for stratification is clearly related to wind speeds. In August and September, wind speed rise from the lower values simulated in June and July. Stratification is relatively minor and of shorter duration for the higher wind speed scenarios. A graphical presentation of the difference between the predicted reservoir temperature and that of the adjacent channel is shown on page C-6. Except during the summer months, DYRESM-simulated reservoir water temperatures are generally lower than measured water temperatures in the adjacent channel.

In 1986, a wet year, the salinity concentrations in the adjacent channels and in the reservoir were low. Simulated reservoir salinity and salinity concentrations measured in the San Joaquin River adjacent to Webb Tract are plotted on page C-7. Salinity concentrations are approximately 140 mg/L at the beginning of the simulation. The concentration declines to approximately 100 mg/L during the fill cycle in late February. The simulated salinity of Webb Reservoir increases slightly in response to higher salinity concentrations in inflow through the end of the simulation and in response to evaporation from the reservoir.

Bacon Island

Results of the CALSIM stage analysis indicate that the Bacon Reservoir contains 18.2 feet of water at the beginning of the simulation (1/1/86). As shown in Figure C-8, the reservoir was filled rapidly at the end of February. Pulsed inflow and outflow volumes are roughly equal from March through May, and there is minimal inflow in July and August. As seen in Figures C-9 through C-11, the degree of thermal stratification is correlated to the applied wind speed. Thermal stratification is predicted for the low wind scenario in July, when average wind speeds fall to approximately 1 m/s. In September, average wind speeds increase to approximately 5 m/s and stratification is eliminated. Only minor, short-lived stratification is simulated to occur for the high wind scenarios. Bacon Reservoir is simulated to be well-mixed for all wind scenarios for the period from September through December.

Throughout January and February of 1986, salinity concentrations in the Middle River were anomalously high at approximately 1100 mg/L (data not shown). Because these high measured salinity values were inconsistent with salinity measured at other Delta locations during this wet period, measured salinity concentrations recorded at the San Joaquin site (adjacent to Webb Tract) were used as model input for January through March 1986. Salinity plots on page

C-7 show that identical salinity concentrations for the adjacent channel were used for both Webb Tract and Bacon Island for January through March. Salinity in Bacon Reservoir reaches a minimum level of approximately 100 mg/L in March and then increases steadily to a maximum of about 180 mg/L at the end of the simulation.

1987 (Dry Year)

The year 1987 was selected by DWR to represent reservoir conditions during a dry year. All plots pertaining to the 1987 simulation are contained in Appendix D. Scaled Brentwood meteorological records plotted on page D-1 were used for all 1987 simulations.

Webb Tract

Results of the CALSIM simulation indicate that the Webb Tract Reservoir contained 20.5 feet of water at the beginning of the simulation (1/1/87). As shown in Figure D-2, pulsed inflow and outflow volumes are approximately equal from January through July. Inflow is suspended in July through August and in October through November. Short periods of weak thermal stratification are predicted for the low wind scenario from June through August, a period of low wind speeds. Thermal stratification is not predicted for either high wind scenario.

Salinity concentrations are primarily influenced by the TDS concentration of the adjacent channel. In January through March, salinity in the San Joaquin River adjacent to Webb Tract is approximately 100 mg/L, and similar salinities are simulated to occur in Webb Reservoir. Throughout 1987, the simulated salinity in Webb Reservoir increases in response to increased salinities in reservoir inflow from the San Joaquin River and in response to evaporation from the reservoir surface. A simulated salinity of approximately 210 mg/L is predicted at the end of the simulation, as shown on pages D-3 through D-5.

Bacon Island

Results of the CALSIM stage analysis indicate that the Bacon Reservoir had a depth of 19.8 feet at the beginning of the simulation (1/1/87). As shown in Figure D-8, pulsed inflow is suspended in April and July. Prior to May 1987, short periods of peak daily average wind speeds as high as 5-10 m/s occur for all wind scenarios, and thermal stratification is not predicted to occur. In June, average wind speeds drop significantly, and DYRESM plots on page D-9 predict very mild, short-lived thermal stratification from May through August for the low wind scenario. Thermal stratification is not predicted to be significant for either high wind scenario.

Salinity concentrations throughout the simulation are plotted in Figure D-7. Salinities were simulated to rise significantly over the simulation period, from values of about 200 mg/L at the start of the simulation to values of about 330 mg/L at the end of the simulation. These simulated increases in salinity occurred primarily in response to increases in the salinity of the inflow to the reservoir (see Figure D-7), with peak inflow salinities of approximately 400 mg/L.

DISCUSSION AND RECOMMENDATIONS

The simulation results presented here demonstrate clearly that stratification and water temperature in the reservoirs is strongly influenced by ambient wind speeds. In the absence of site-specific wind monitoring data, it is not possible to know exactly the wind speeds at the proposed reservoir locations. For this reason, a range of wind speeds has been evaluated, and the simulated reservoir water temperature and stratification have been predicted for a range of potential wind speeds. It is anticipated that actual field wind speeds within the Delta will fall somewhere between the low and high values used in the modeling. Many of the differences between measured wind speed at various stations in the Delta are likely caused by local differences in topography (e.g., there may be a "sheltering effect" at the Brentwood site). The best method for resolving these discrepancies and evaluating wind speed at the reservoir locations would be to install weather stations. Weather stations that measure wind speed and direction could be installed at the reservoir sites for a few thousand dollars. Similarly, if detailed data were available, an evaluation of the variation in wind speed over the course of a day could be made in order to adjust the model results to site-specific conditions and to reflect these variations more accurately.

Although simulated wind speeds are the most important meteorological influence on stratification and simulated water temperatures within the reservoirs, many other factors affect these conditions. Other factors include ambient conditions (air temperature, humidity, etc.) and operational factors (inflows and outflows, reservoir depths). While beyond the scope of the work presented here, additional work could be conducted to determine the importance of these other parameters in the development of stratification.

In addition, the work presented here examined conditions for three distinct model years (1979, 1986, and 1987). These years were selected by DWR to represent a likely range of hydrologic and reservoir operating conditions. However, as noted in this report, data extrapolations were necessary to create model input files, as available meteorological and water temperature data for these years were occasionally missing or incomplete. In addition, no analysis was conducted to determine whether or not the meteorological conditions that occurred in these three years were representative of the full range of meteorological conditions that would be likely to occur over a longer time period. Nonetheless, it is expected that the meteorological conditions used in this modeling will capture most of the generally expected range of conditions.

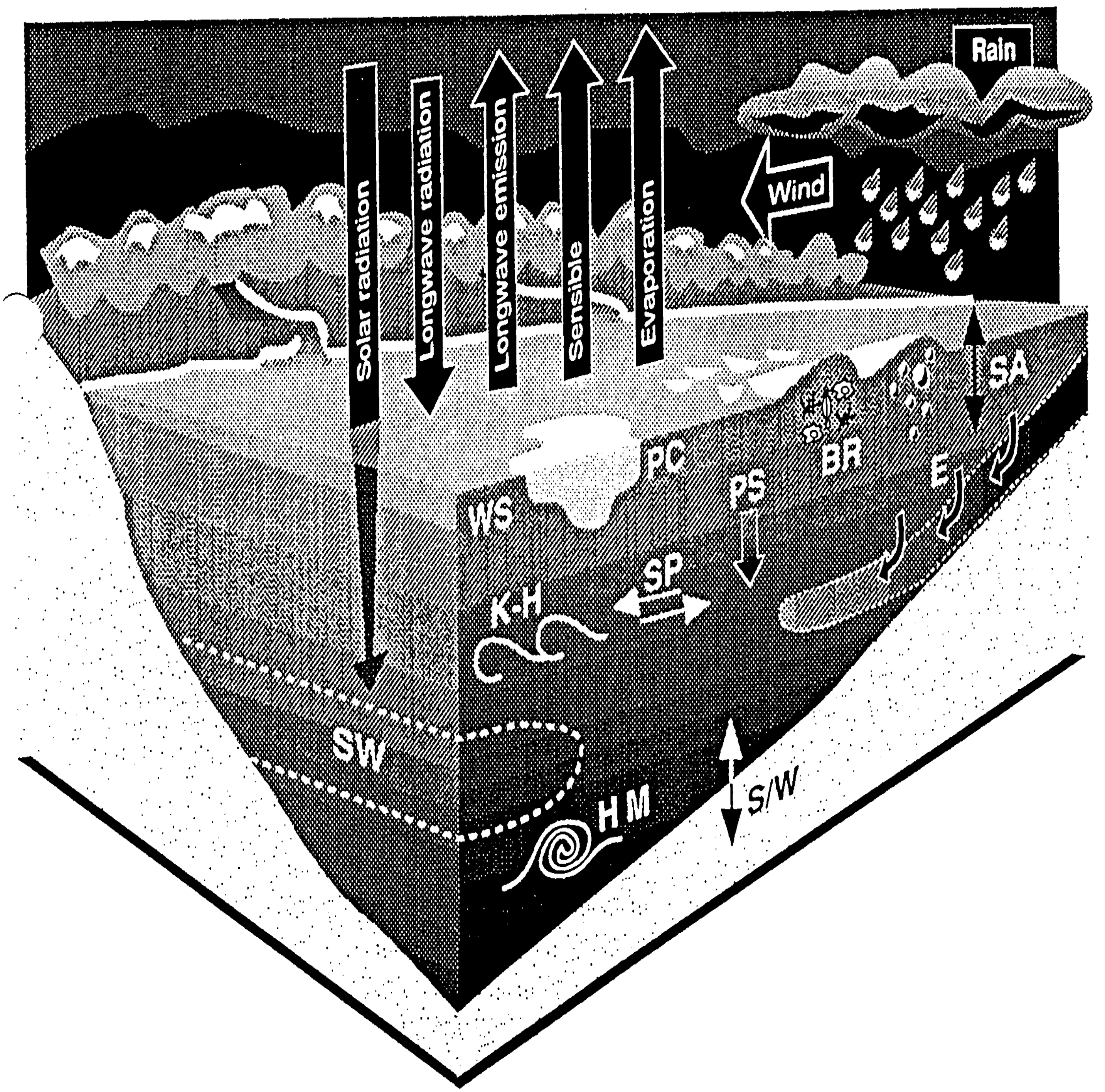
Conditions that would enhance stratification (an extended period of low wind speeds and high solar flux) are unlikely to occur in the Delta. If appropriate, additional modeling and data analysis could be conducted to address these issues.

Finally, the conclusions presented in this report are necessarily limited in scope and extent. While the assumptions made in this report concerning one-dimensionality and the use of daily time steps for input data are appropriate to support the conclusions presented here, these assumptions may not be appropriate in the evaluation of other conditions and other reservoir characteristics. In particular, the results presented here are not appropriate as the basis for conclusions on biological, chemical, or ecological processes within these proposed reservoirs, as many of these processes occur on shorter time and spatial scales than used in this modeling.

ACKNOWLEDGMENTS

Flow Science is grateful for thoughtful and constructive comments received from two anonymous peer reviewers. In addition, Flow Science would like to acknowledge assistance from DWR personnel in locating and obtaining measured data for use in these model simulations, and for constructive discussions as the modeling was conducted.

DYRESM-WQ Model



The one-dimensional DYRESM model showing horizontal layers and the major internal and external forcing functions used in the model. Internal processes include wind shear (WS), penetrative convection (PC), Kelvin Helmhöltz billowing (K-H), shear production at the thermocline (SP), hypolimnetic mixing (HM) and inflow entrainment (E). The outflow withdrawal layer is represented by SW (selectivewithdrawal).

Figure 1

Location of Meteorological Data Sites

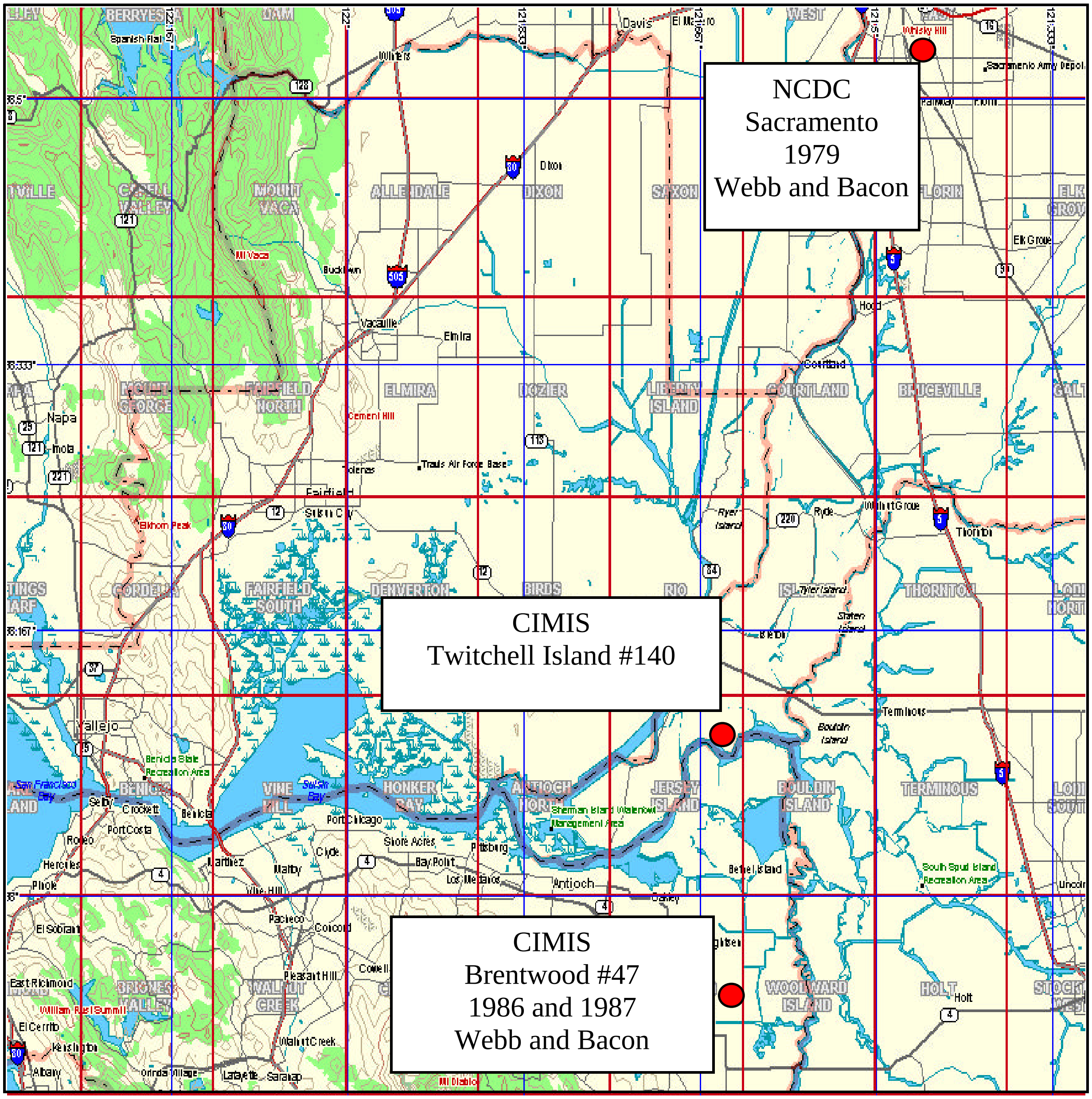


Figure 2

Webb Tract
Capacity Curve

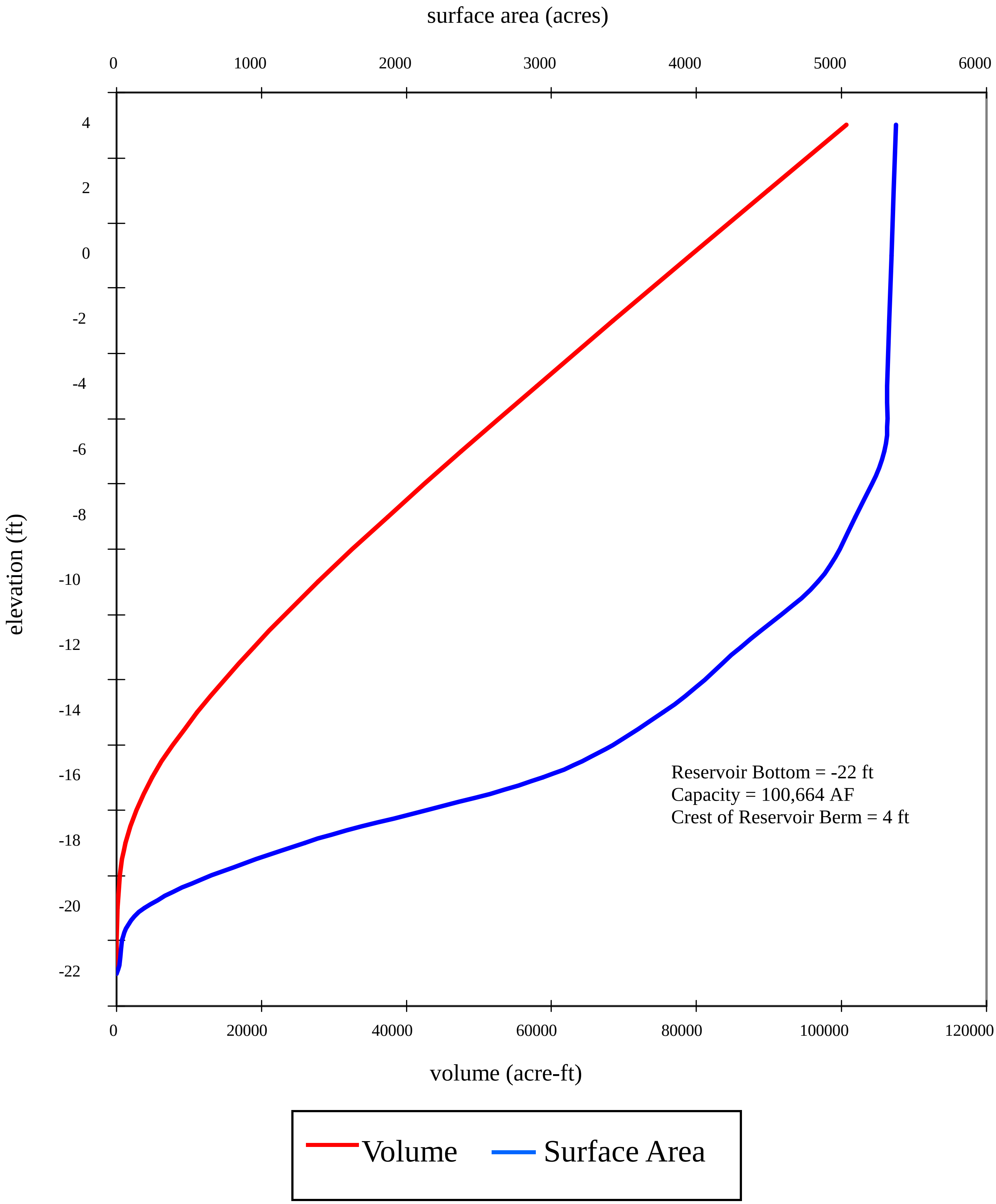


Figure 3

Bacon Island
Capacity Curve

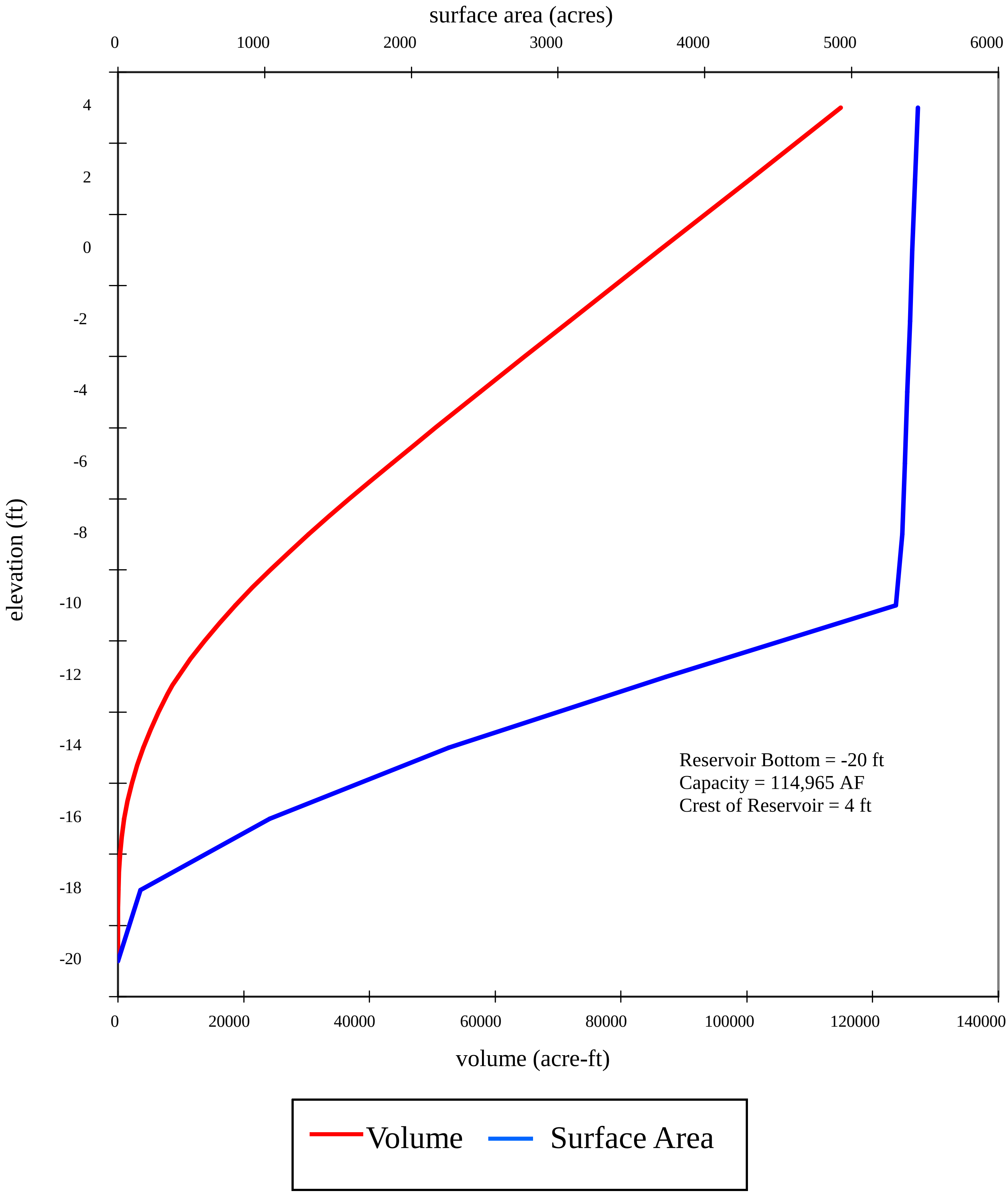


Figure 4

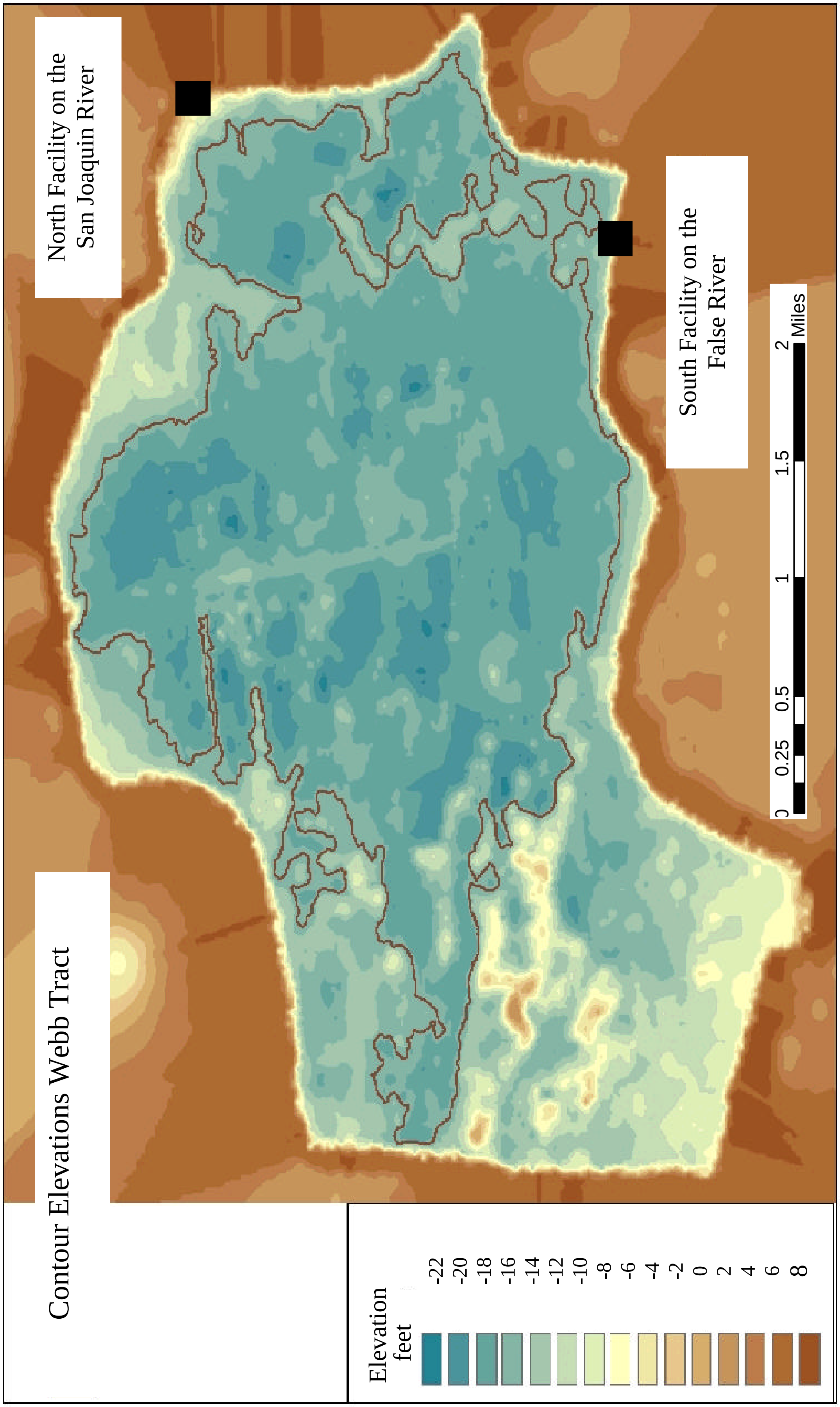

Contour Elevations Webb Tract
North Facility on the San Joaquin River
South Facility on the False River
0
0.25
0.5
1
1.5
2
Miles
Elevation feet
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8

Figure 5

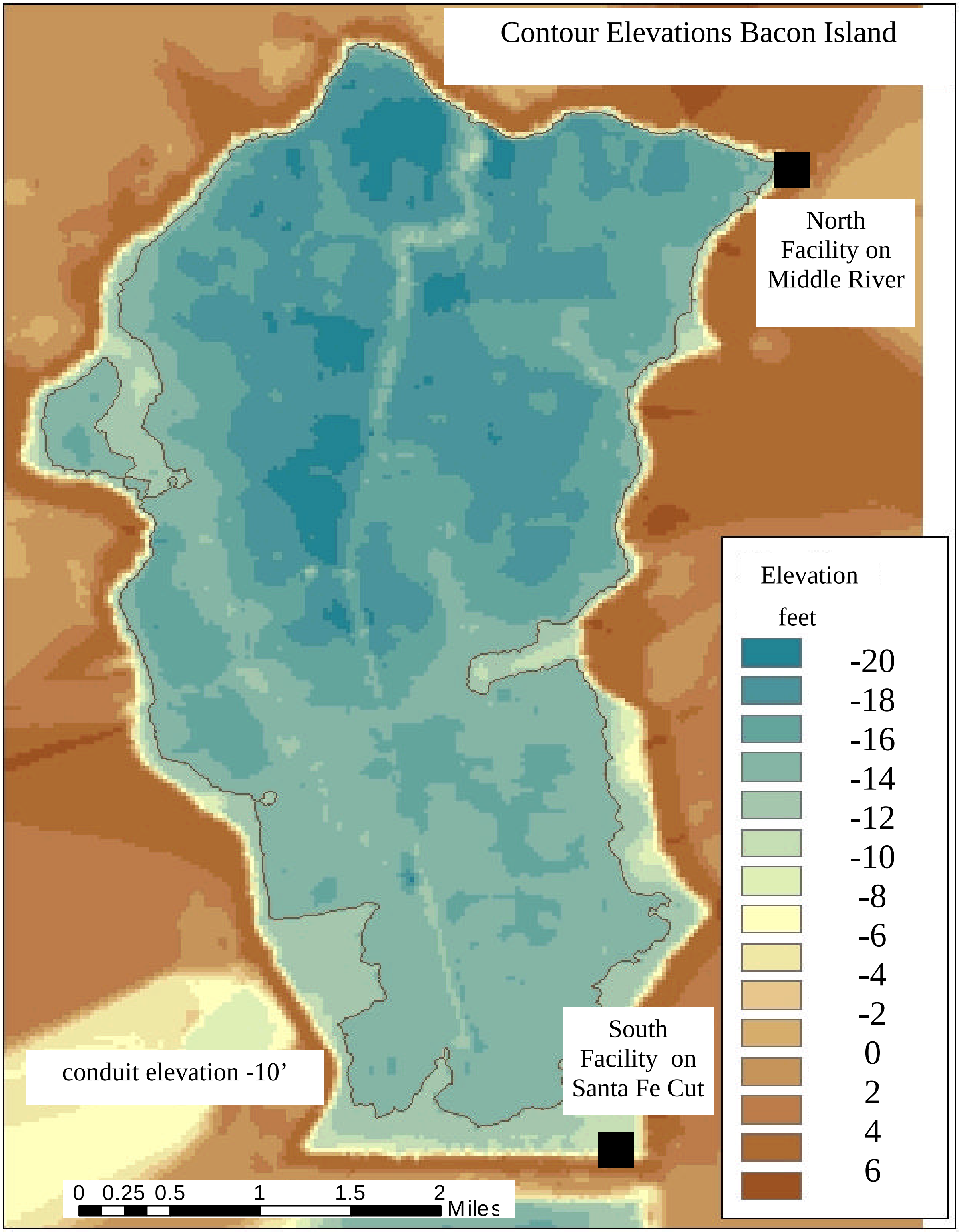
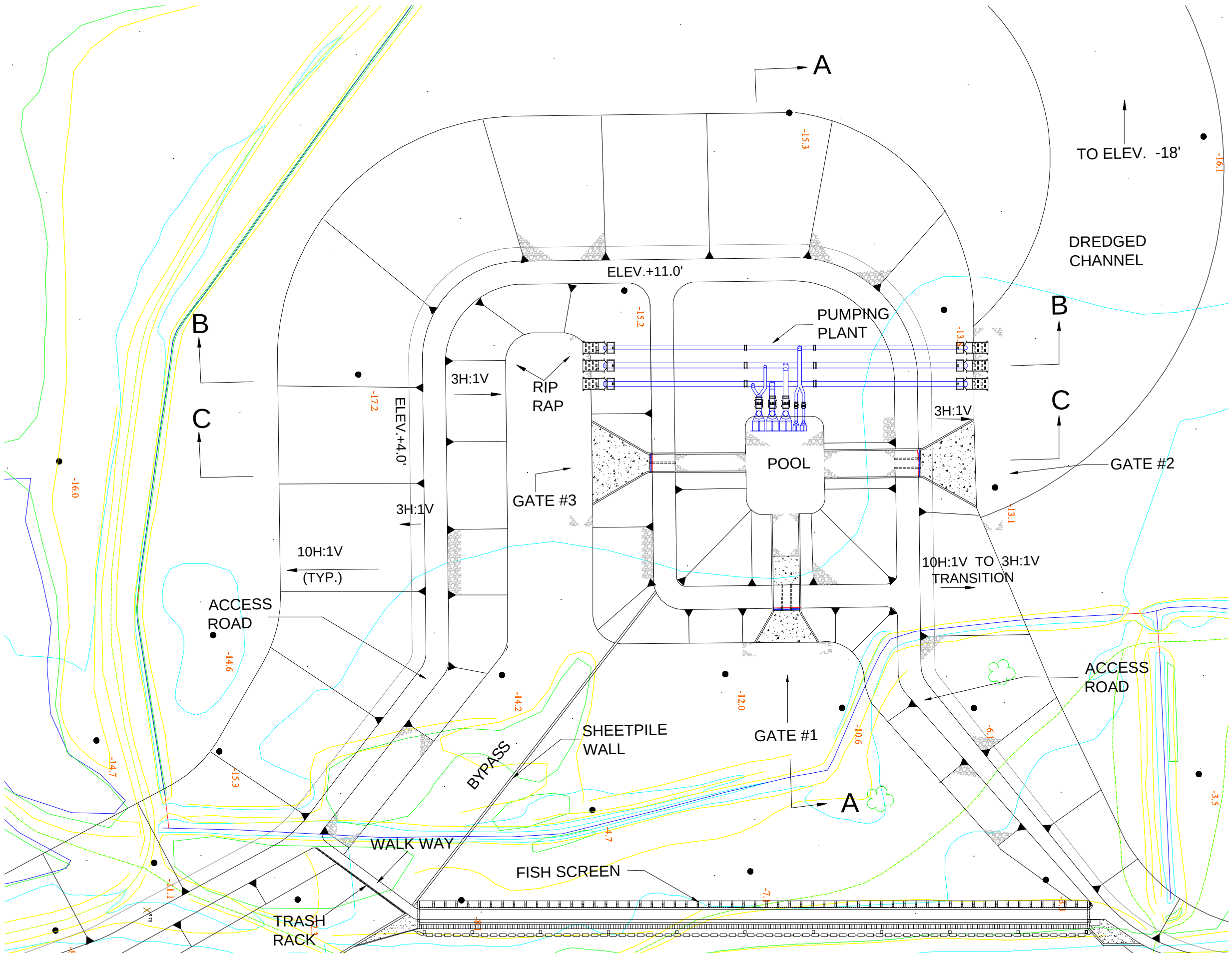

Contour Elevations Bacon Island
North Facility on Middle River
Elevation feet
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
South Facility on Santa Fe Cut
conduit elevation -10’
0 0.25 0.5 1 1.5 2 Miles

Figure 6

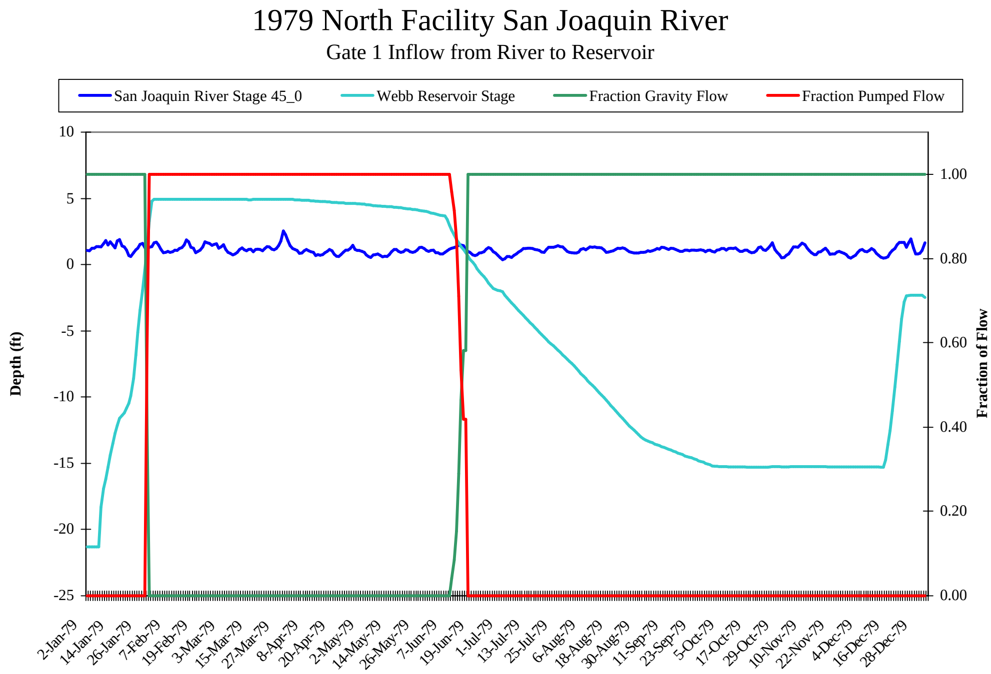
Schematic of Integrated Facility



Webb Tract
San Joaquin River Integrated Facility

Figure 7

Flow Distribution
1979 Webb Tract



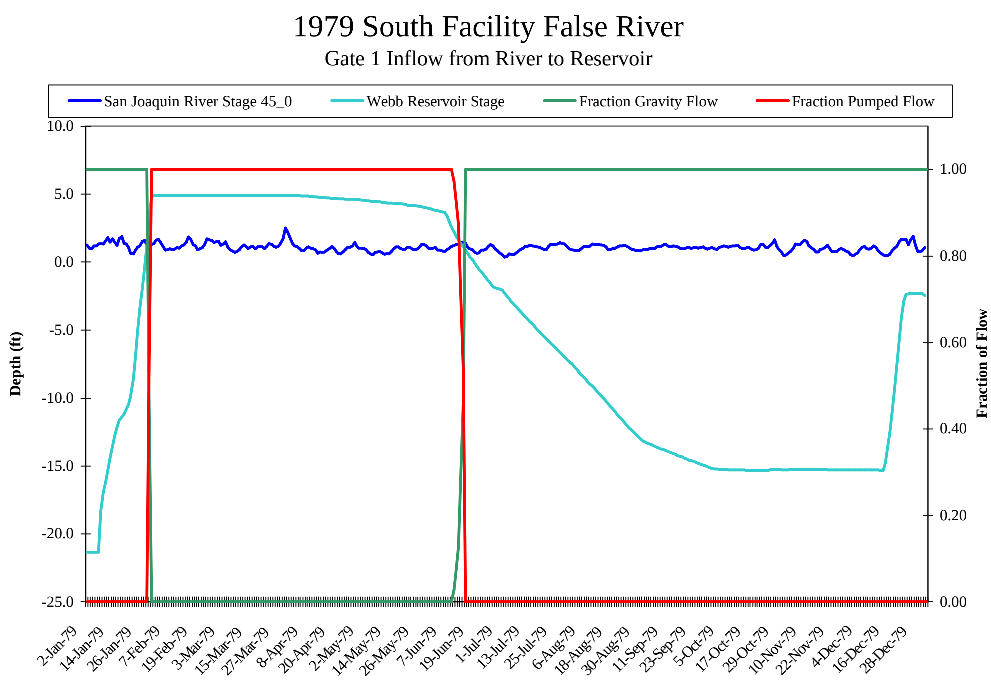
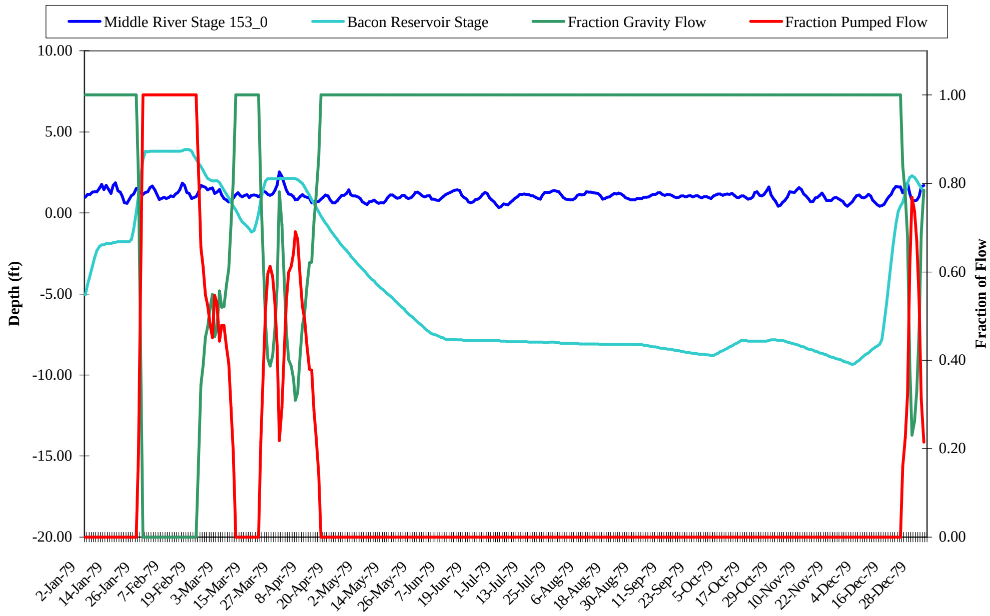


Figure 8

Flow Distribution
1979 Bacon Island



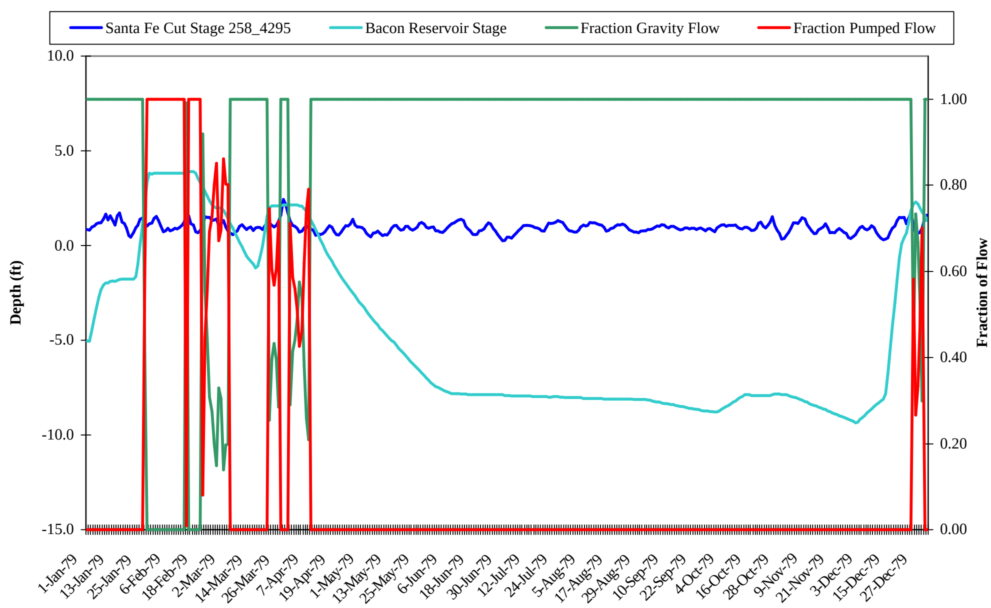
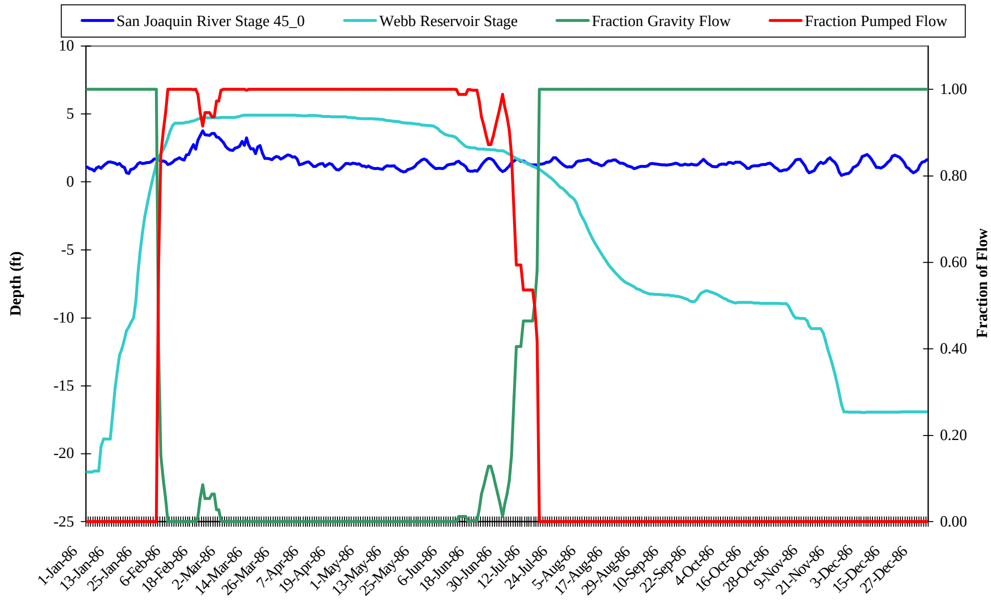


Figure 9

Flow Distribution
1986 Webb Tract

1986 North Facility San Joaquin River
Gate 1 Inflow from River to Reservoir



1986 South Facility False River
Gate 1 Inflow from River to Reservoir

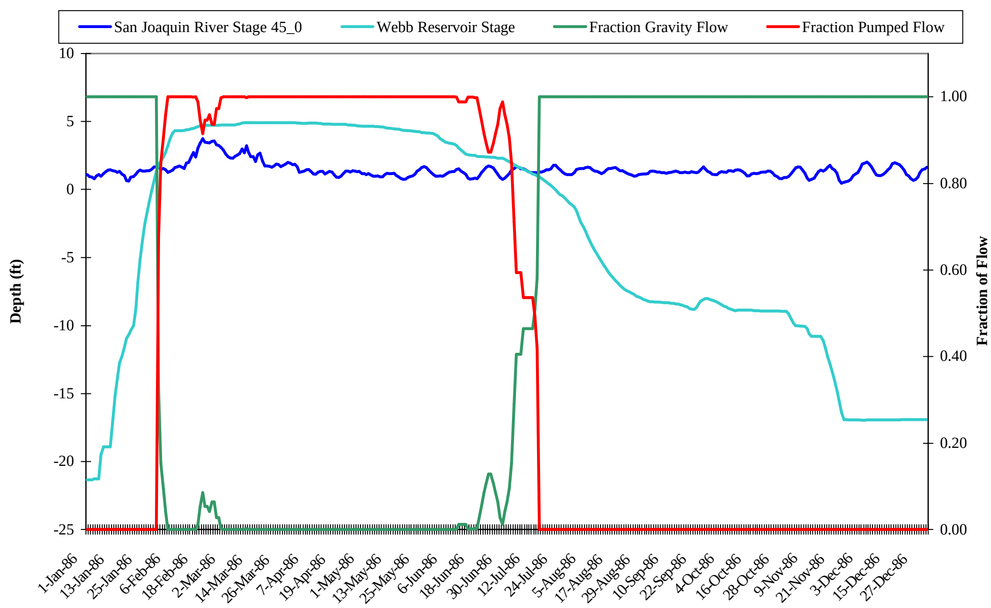
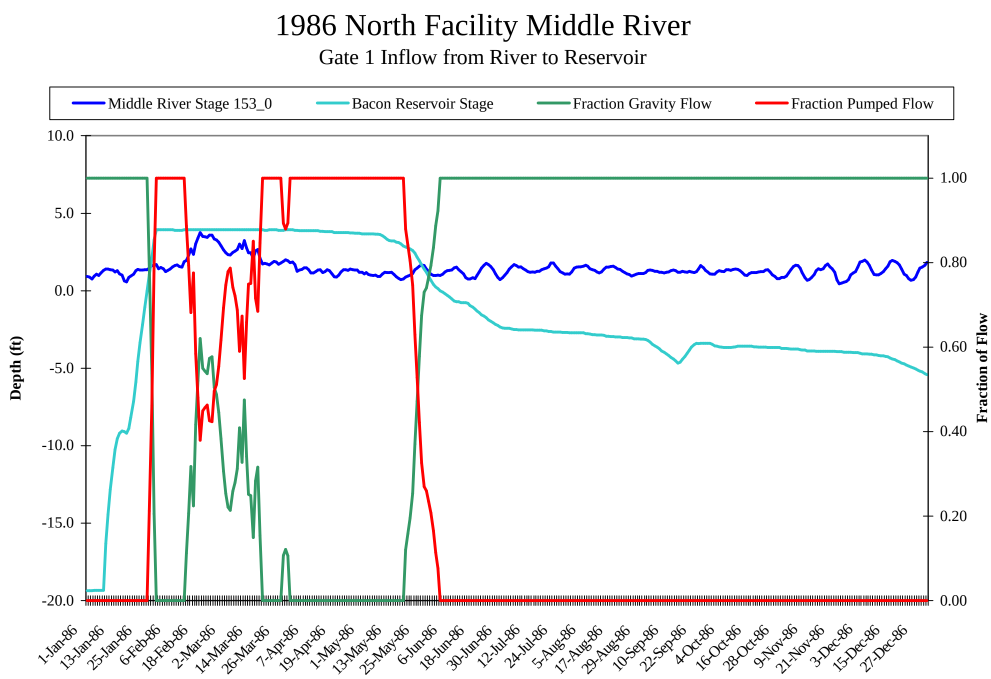


Figure 10

Flow Distribution
1986 Bacon Island



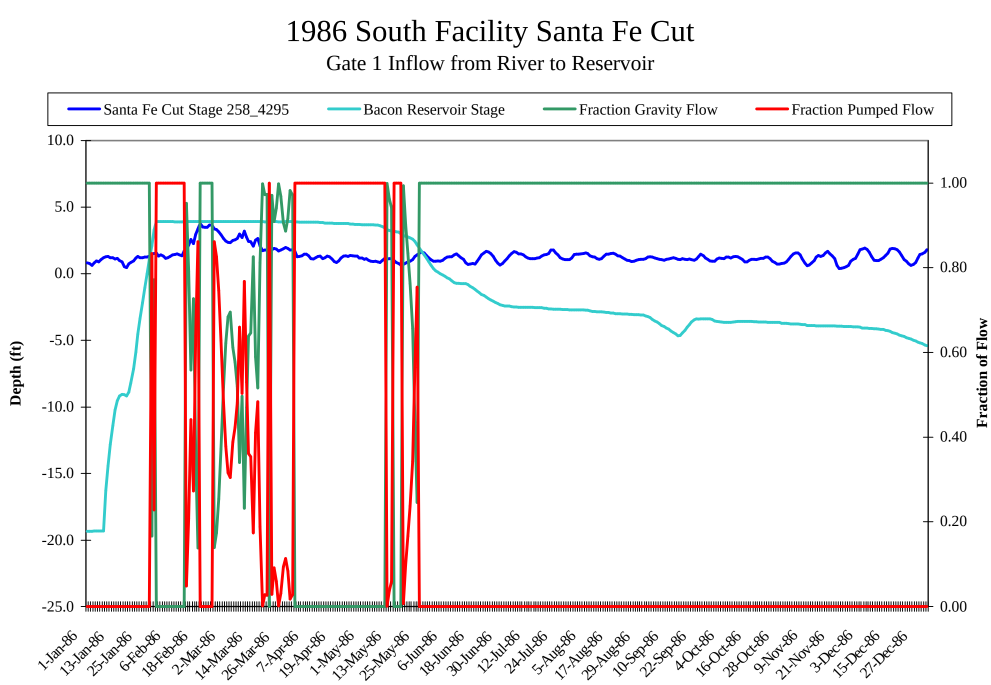
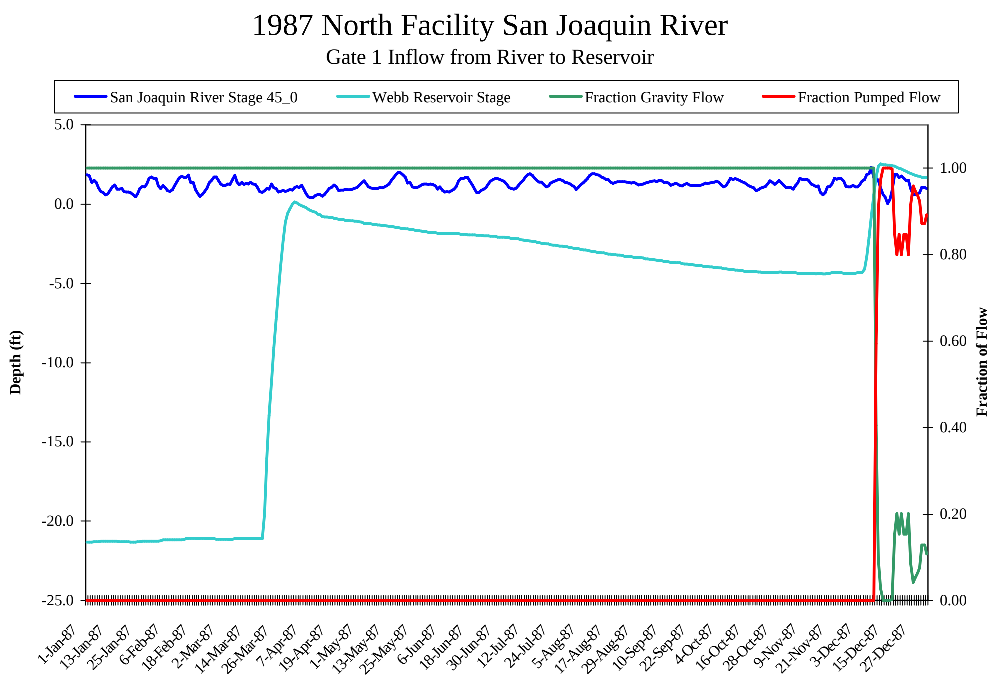


Figure 11

Flow Distribution
1987 Webb Tract



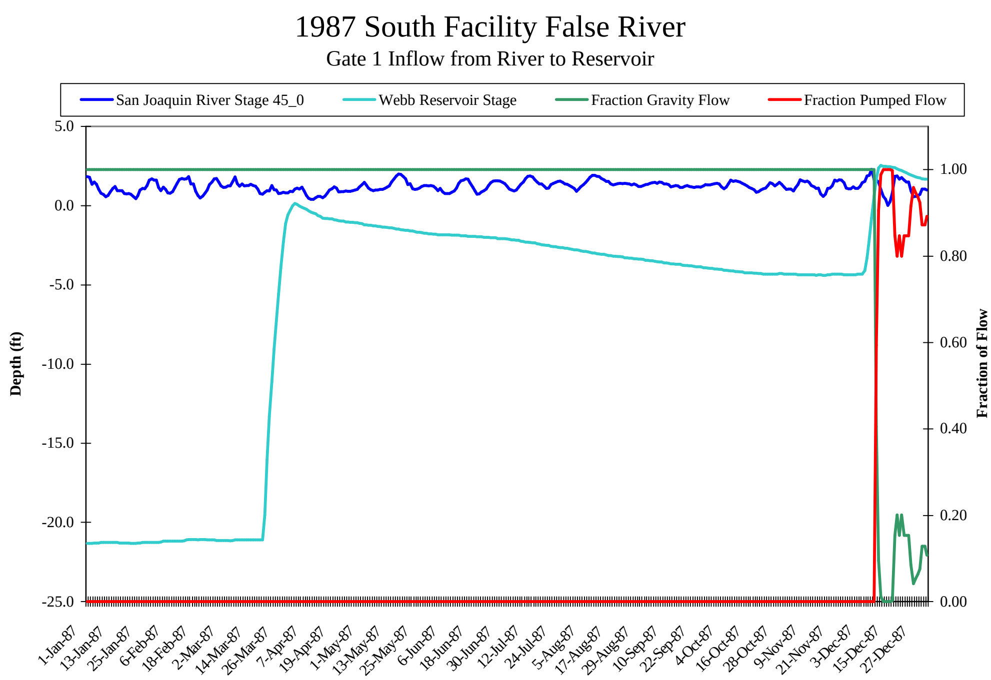
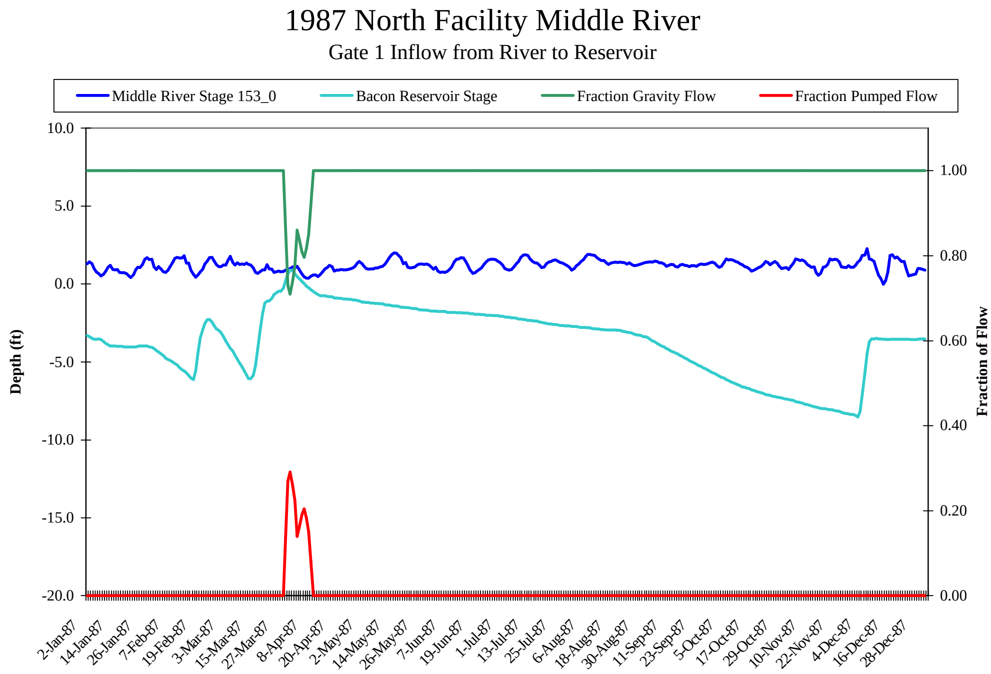


Figure 12

Flow Distribution
1987 Bacon Island



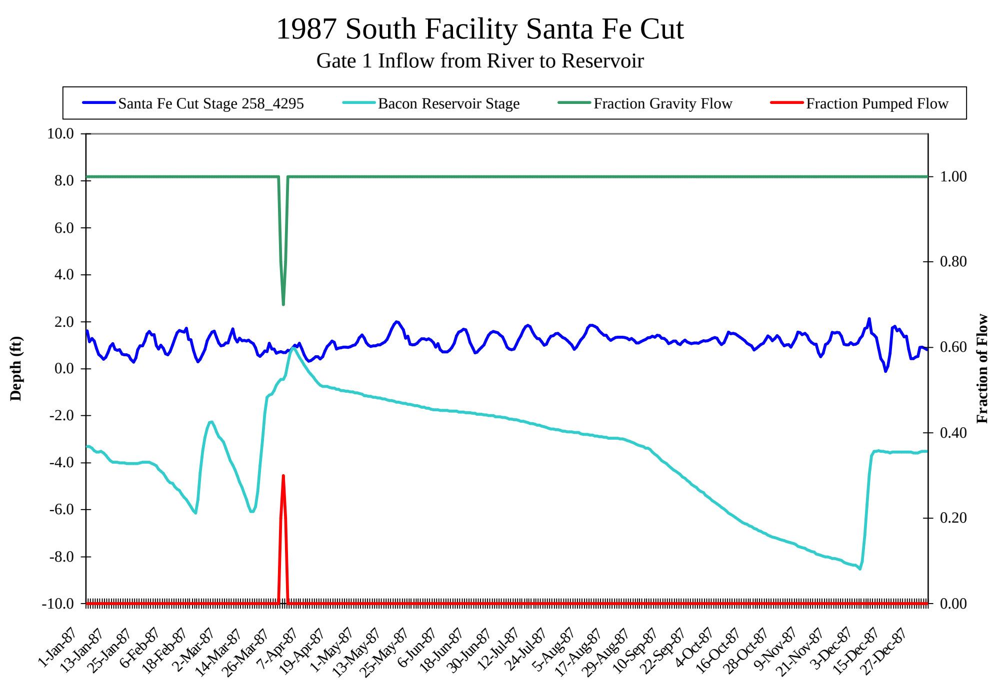


Figure 13

Location of EC Data and DWR Algorithm Development Sites

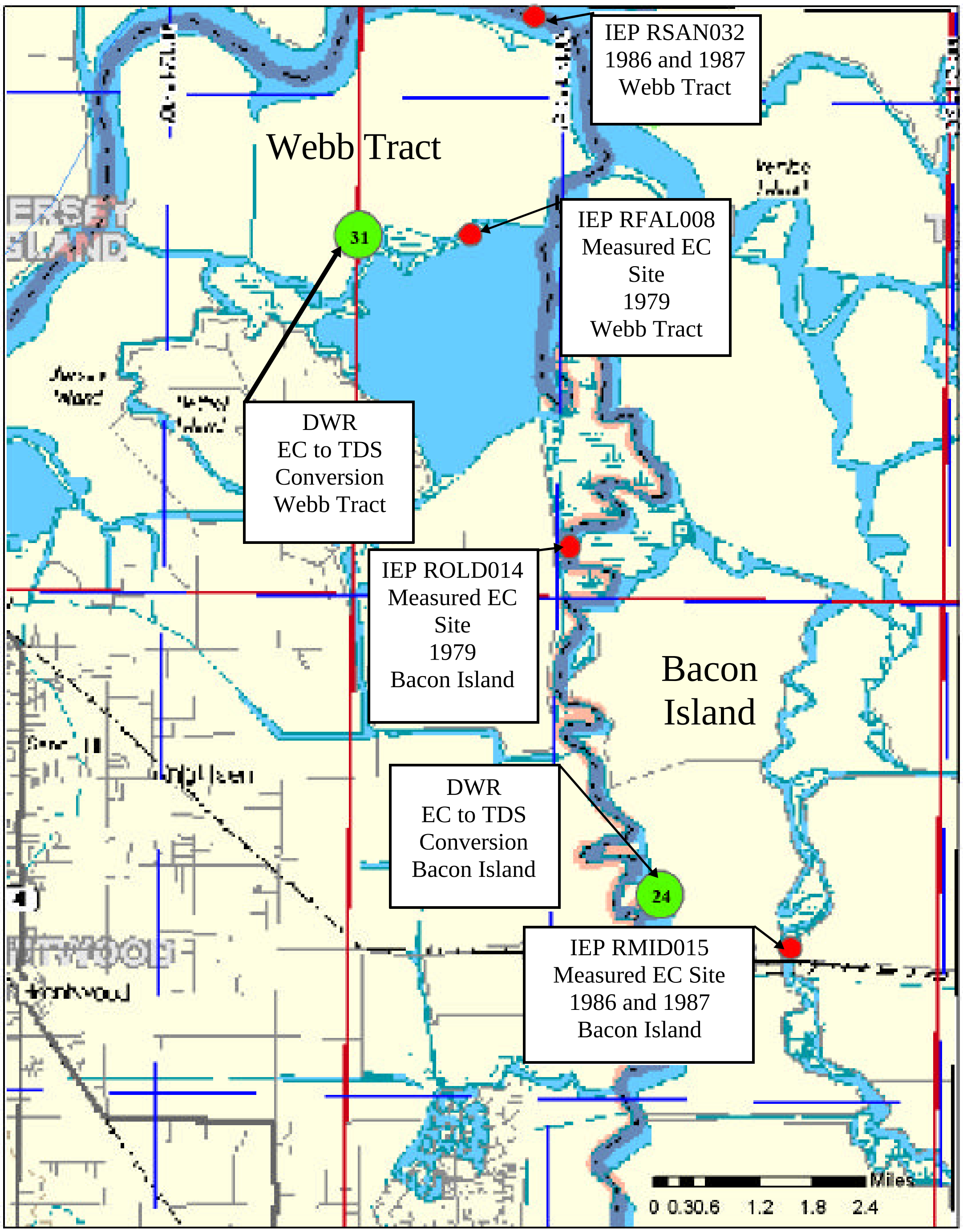


Figure 14

Location of River Temperature Data Sites

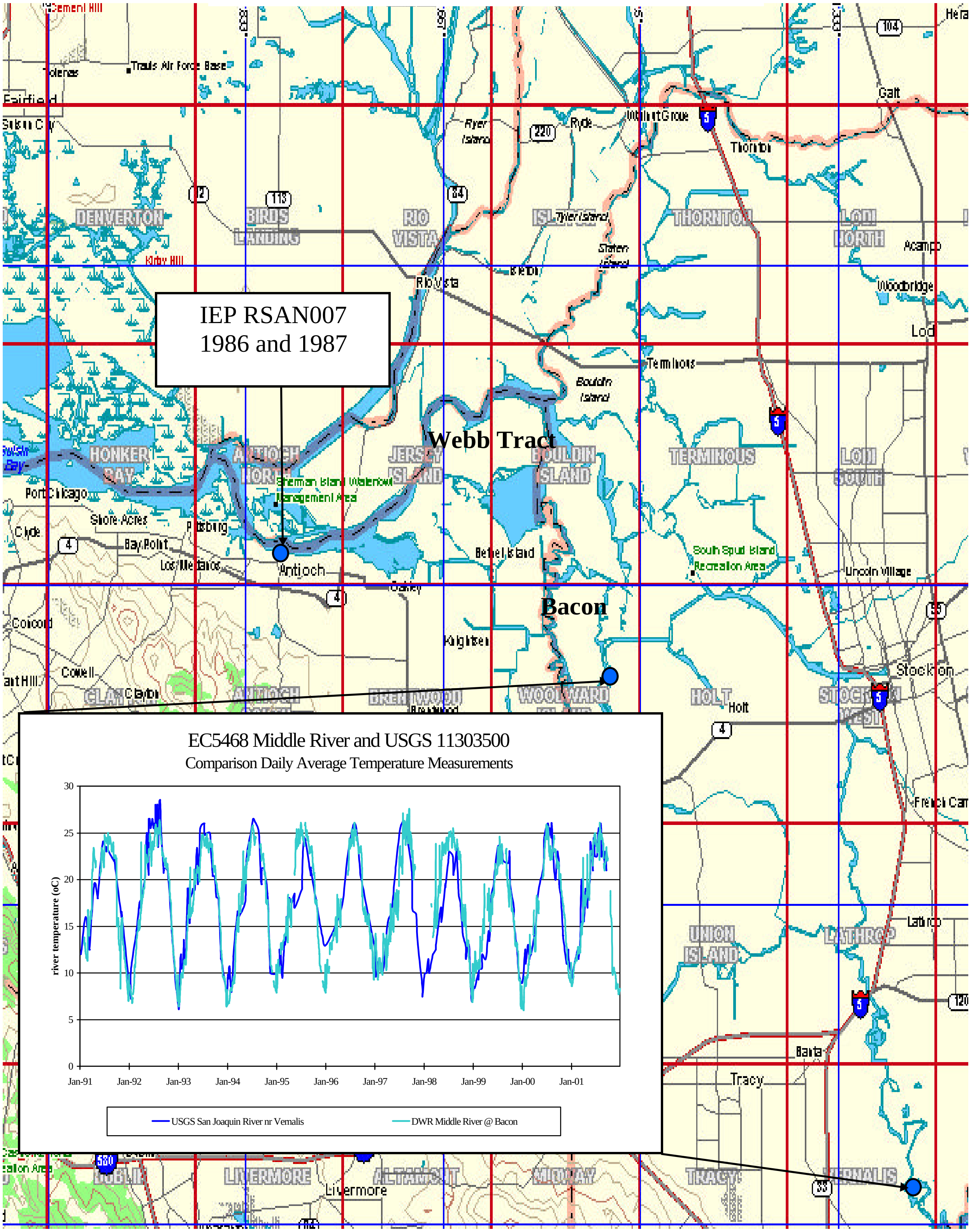


Figure 15

Delta River Temperature
Data Collected

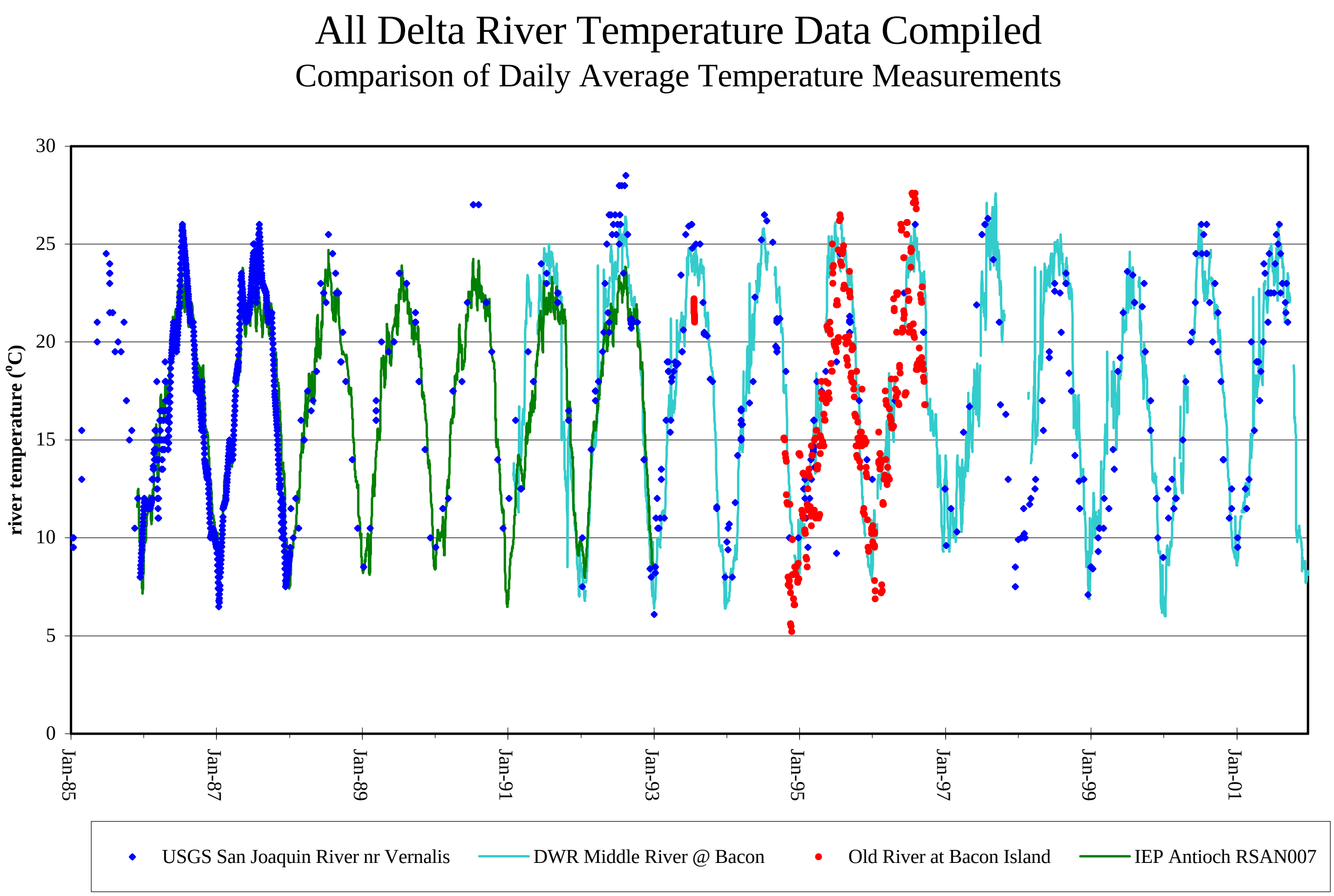


Figure 16

Location of River Temperature
Data Sites

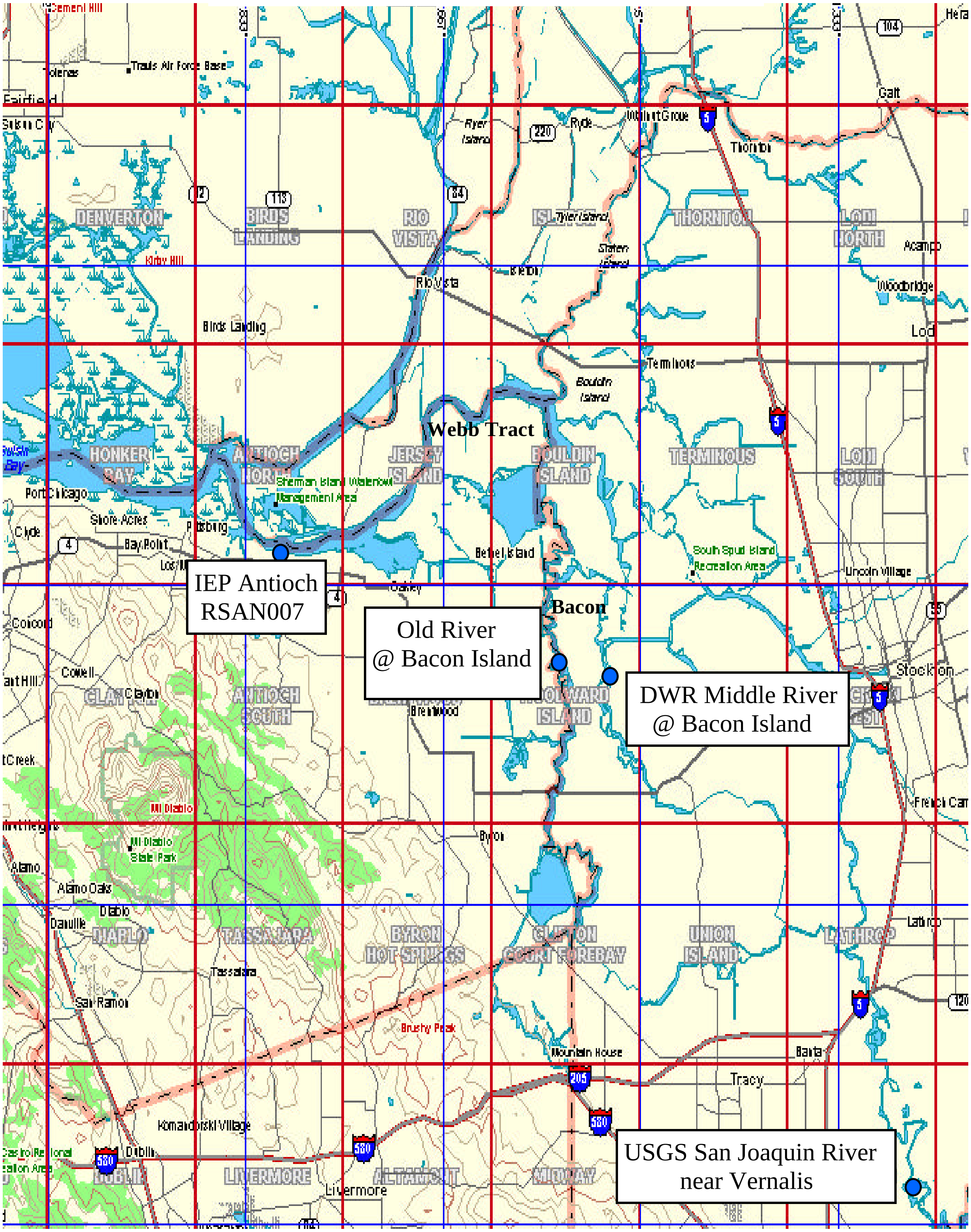
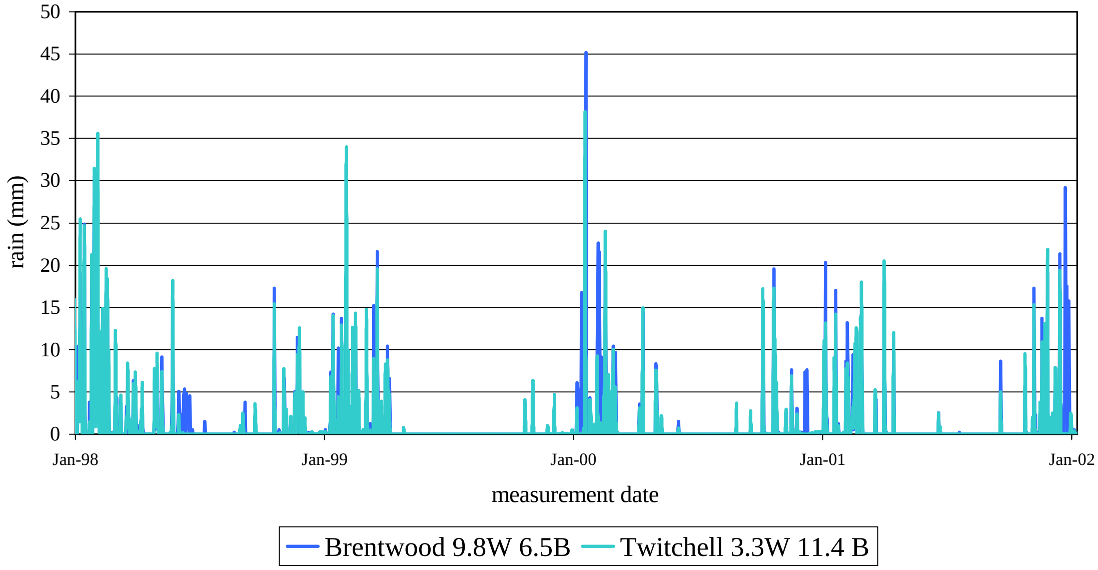


Figure 17

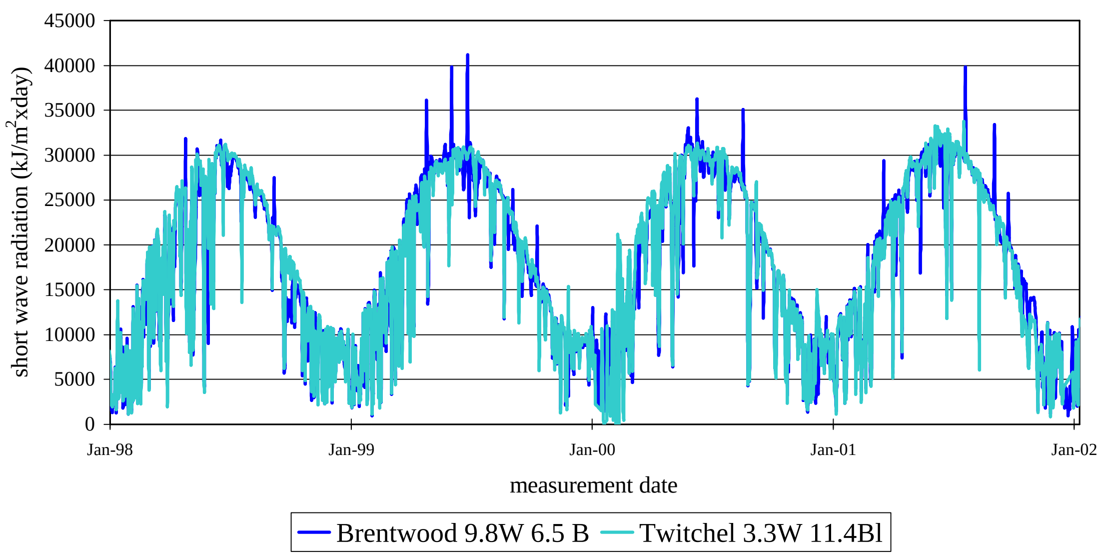
Appendix A
Meteorological Sensitivity Plots

Sensitivity Analysis
1998-2002 CIMIS Brentwood to Twitchell

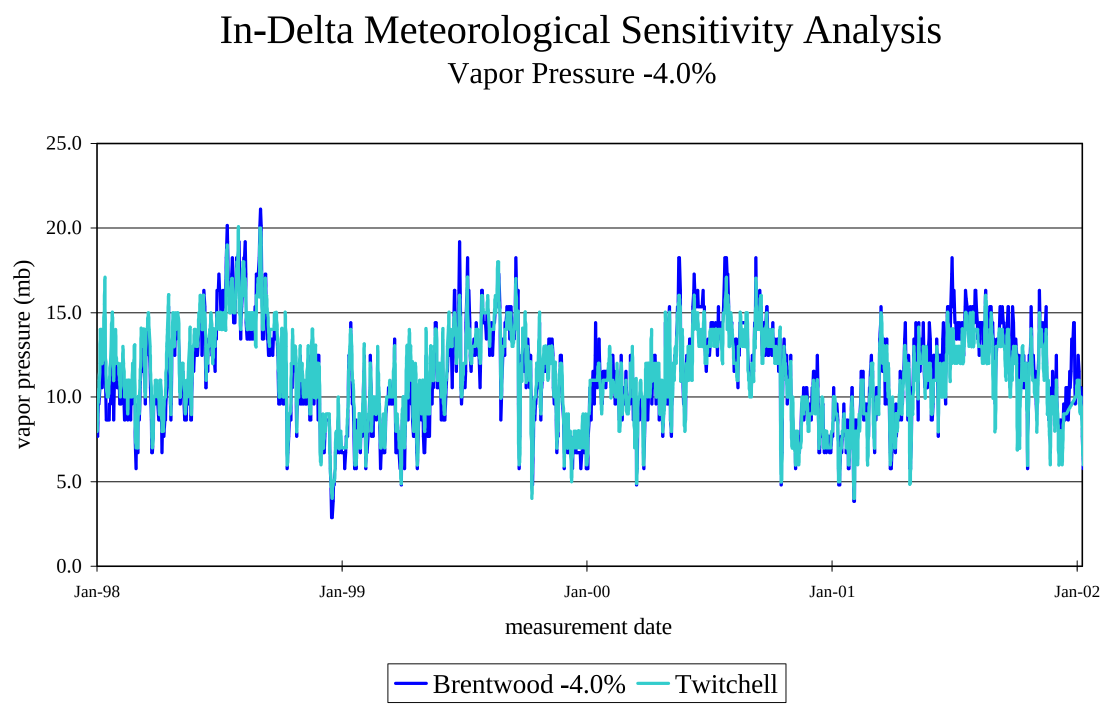
In-Delta Meteorological Sensitivity Analysis
1998-2002 Rain 0%

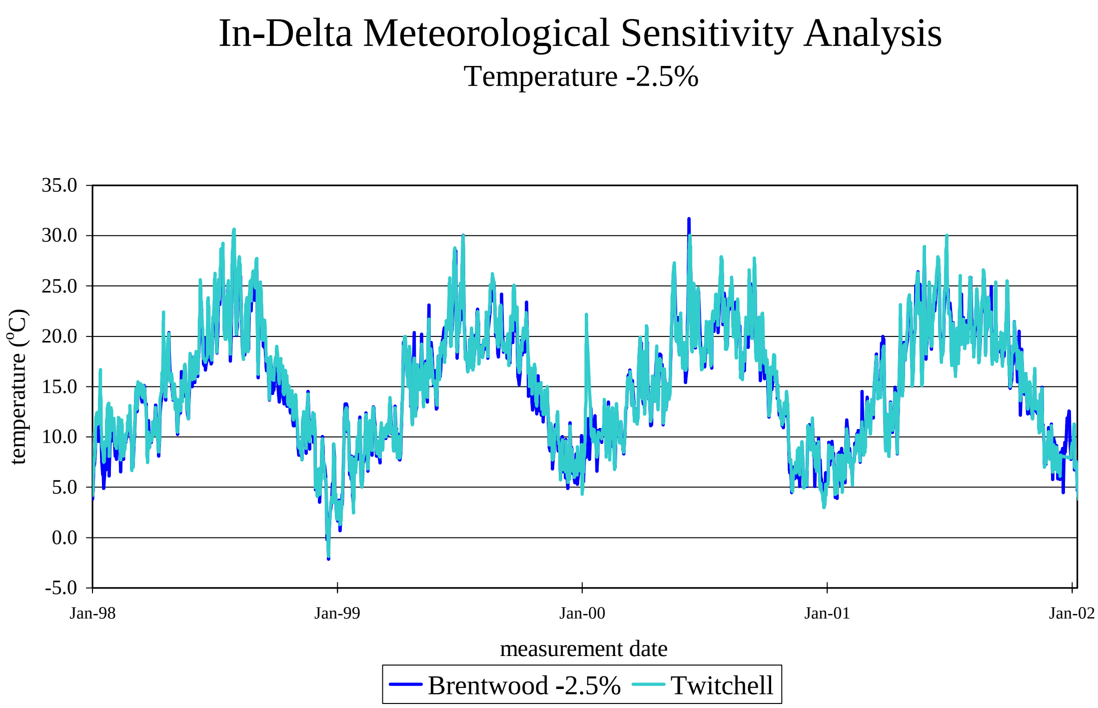


In-Delta Meteorological Sensitivity Analysis
Solar Radiation 0%



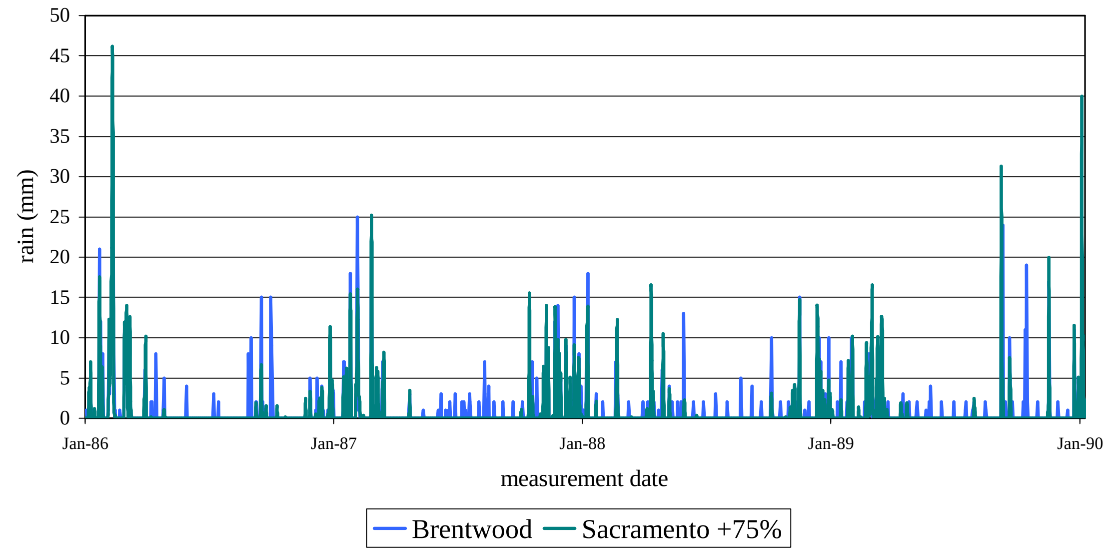
Sensitivity Analysis
1998-2002 CIMIS Brentwood to Twitchell



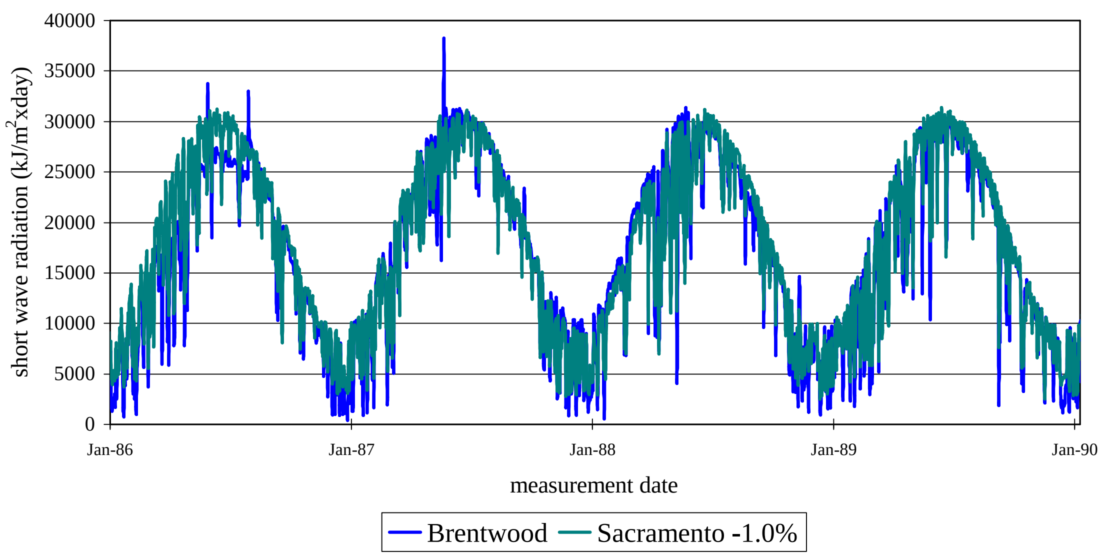


Sensitivity Analysis
1986-1990 CIMIS Brentwood to NCDC Sacramento

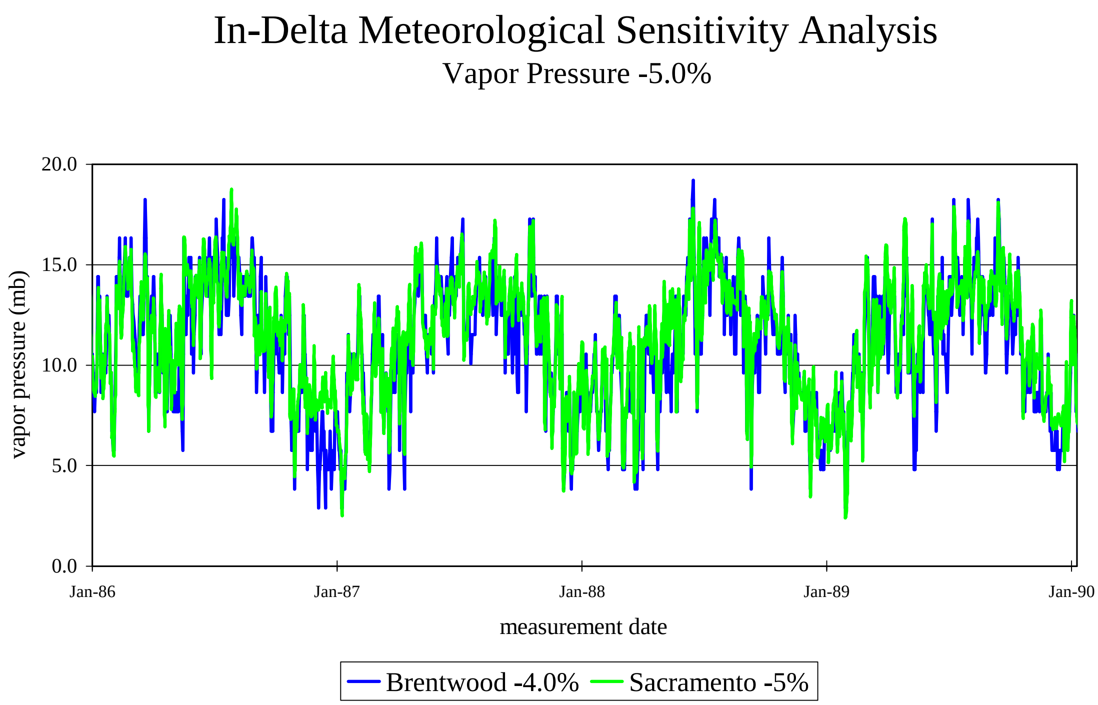
In-Delta Meteorological Sensitivity Analysis
1986-1990 Rain +75%

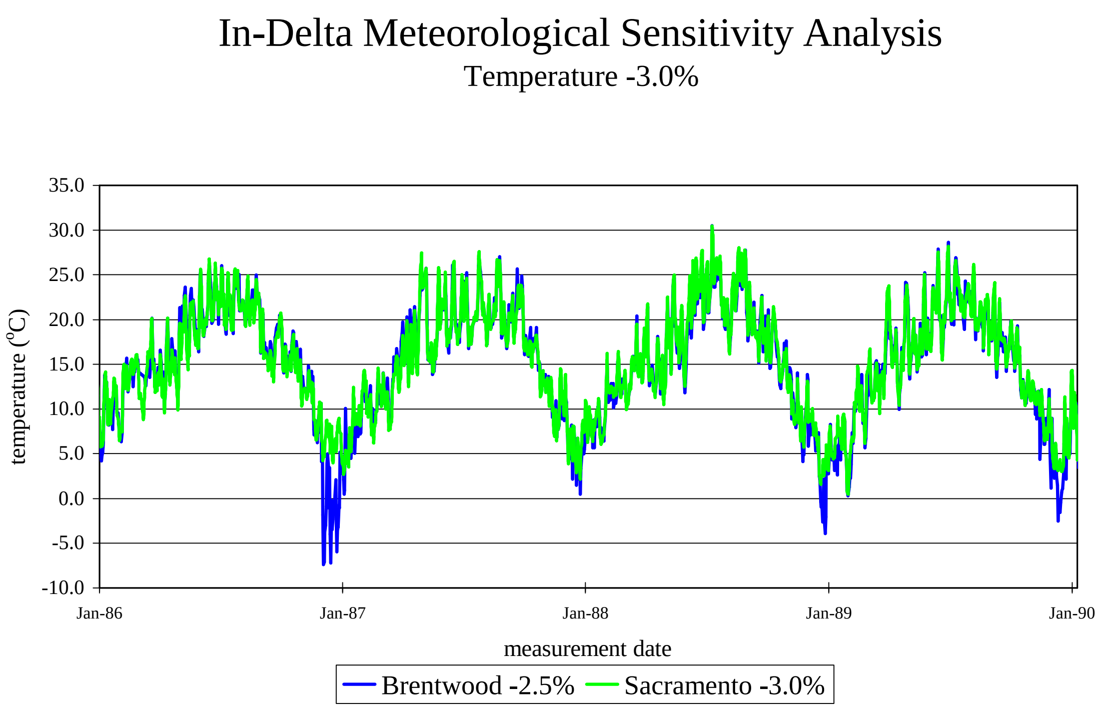


In-Delta Meteorological Sensitivity Analysis
Solar Radiation -1.0%



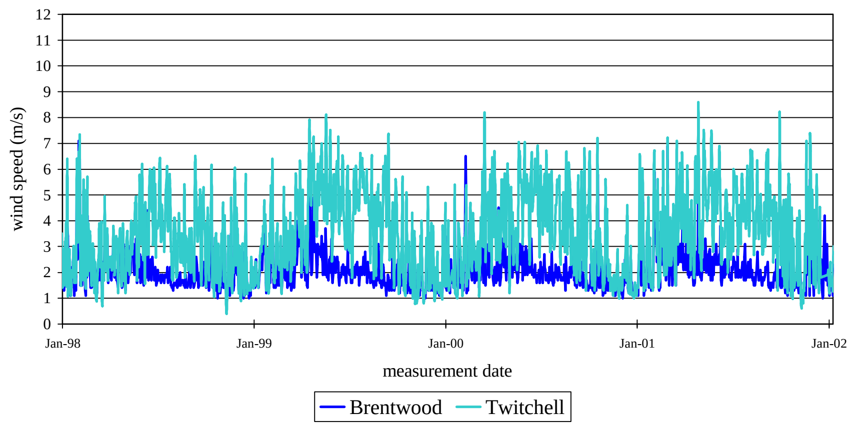
Sensitivity Analysis
1986-1990 CIMIS Brentwood to NCDC Sacramento



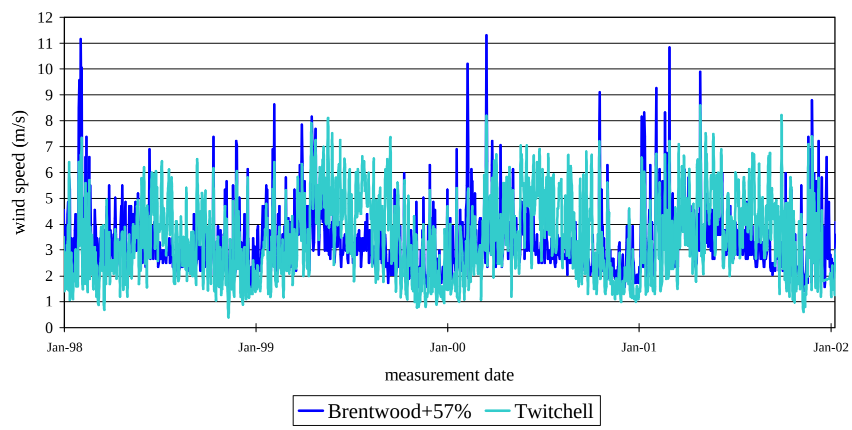


Sensitivity Analysis
Wind Speed

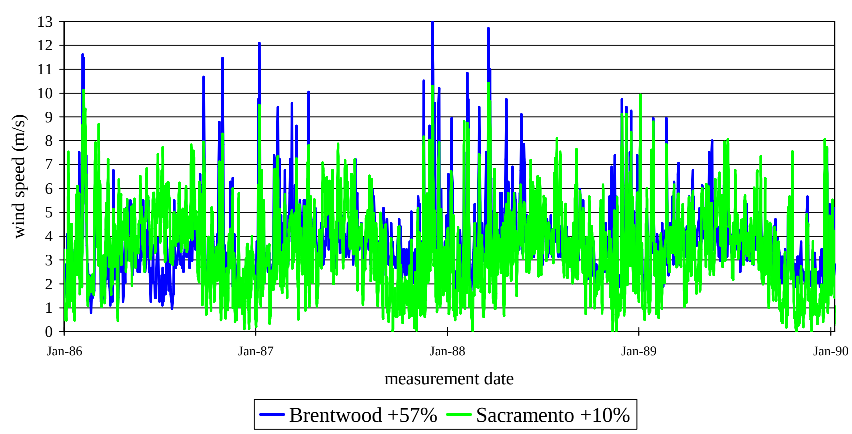
In-Delta Meteorological Sensitivity Analysis
1998-2002 Recorded Wind Data



In-Delta Meteorological Sensitivity Analysis
1998-2002 Recorded Wind Data

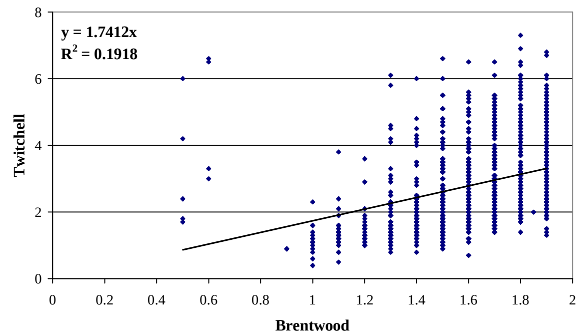


In-Delta Meteorological Sensitivity Analysis
1986-1990 Wind Adjusted Data

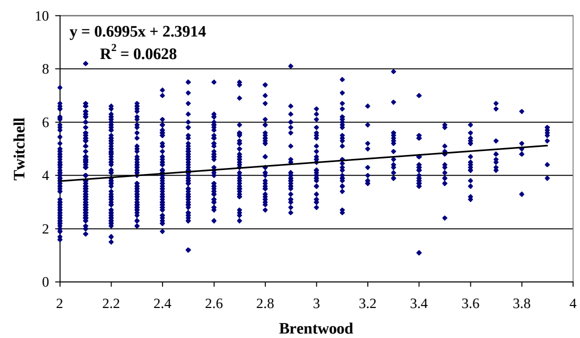


Sensitivity Analysis
1986 and 1987 High Wind Condition

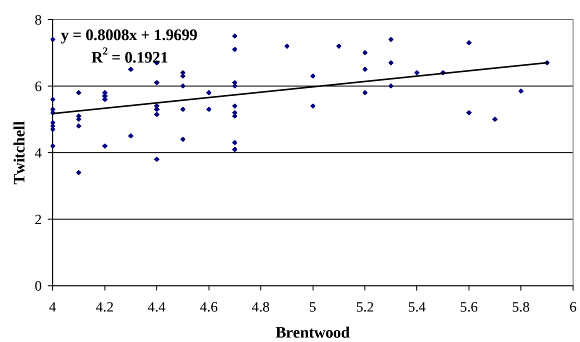
Bin 1 less than 2 for Brentwood Avg wSpd (m/s)



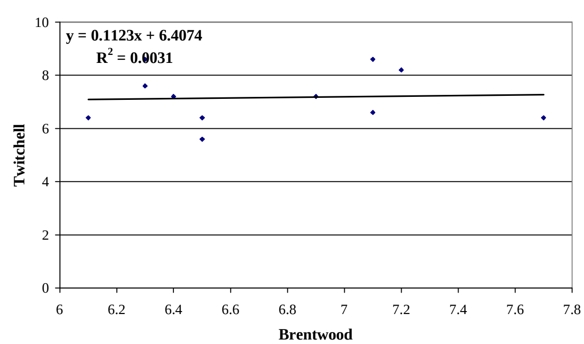
Bin 2 two to four for Brentwood Avg wSpd (m/s)



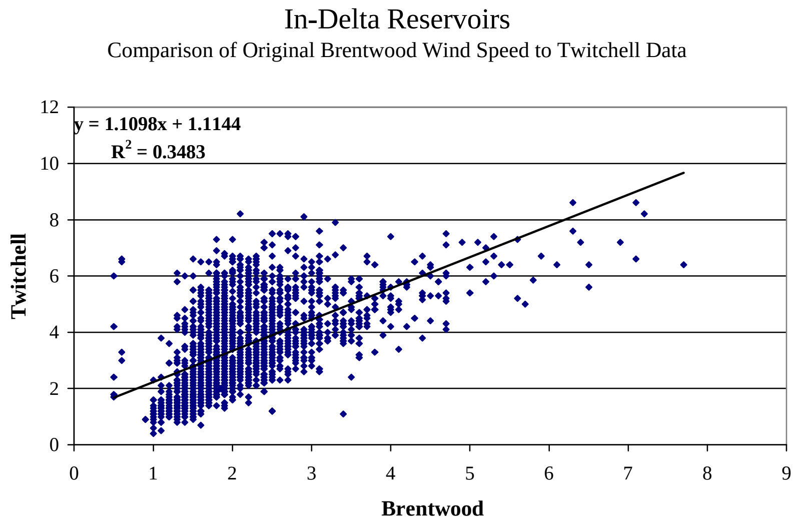
Bin 3 four to six for Brentwood Avg wSpd (m/s)

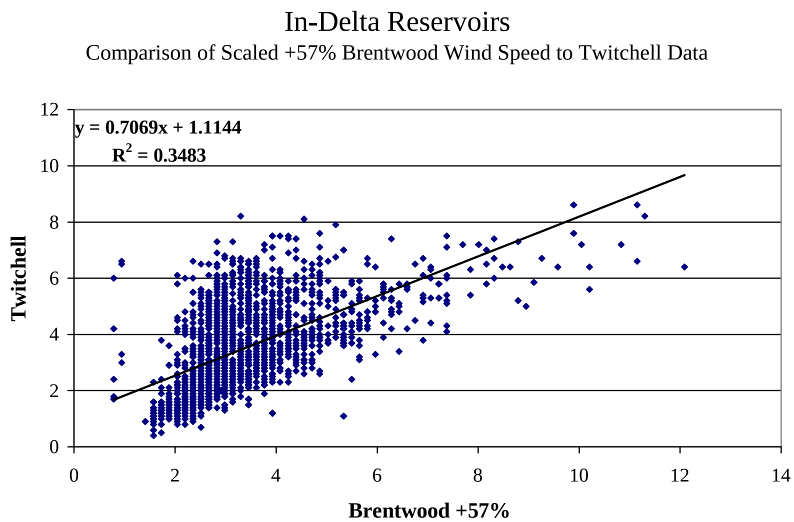


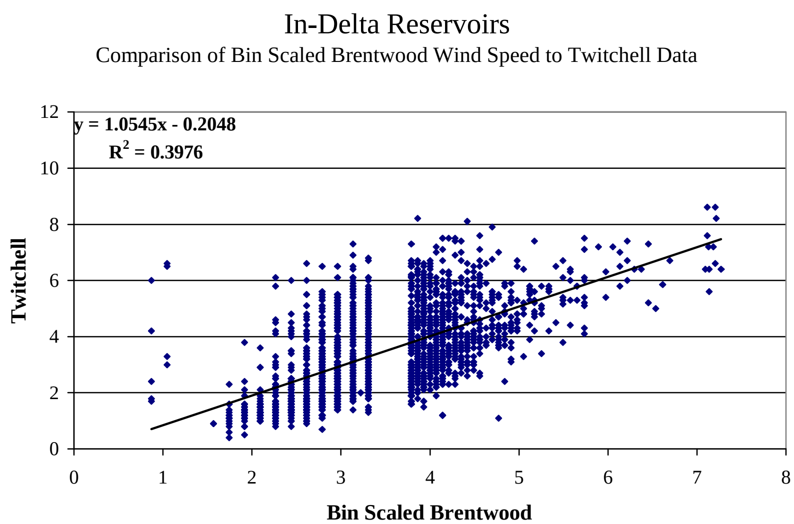
Bin 4 greater than 6 for Twitchell Avg wSpd (m/s)



Sensitivity Analysis
Wind Speed



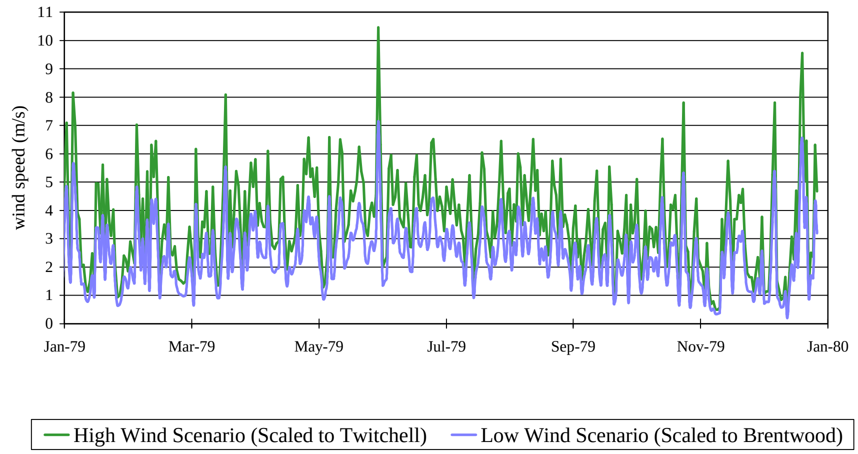




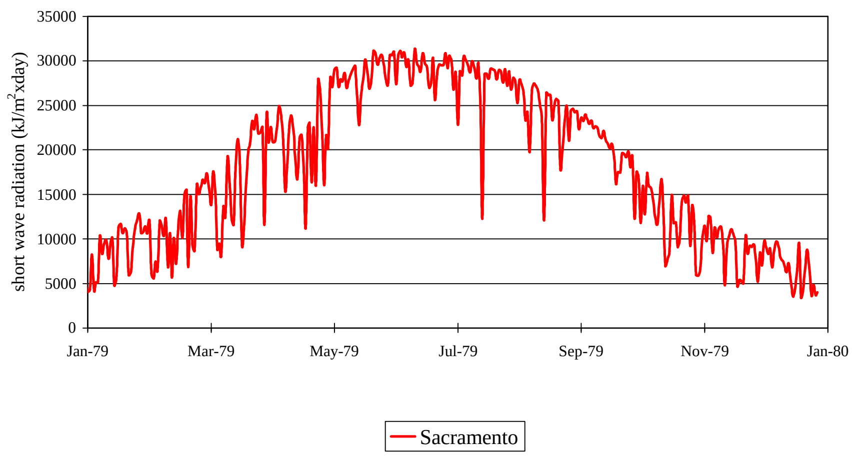
Appendix B
1979 (Typical Year) Simulation

DYRESM
1979 Meteorological Data

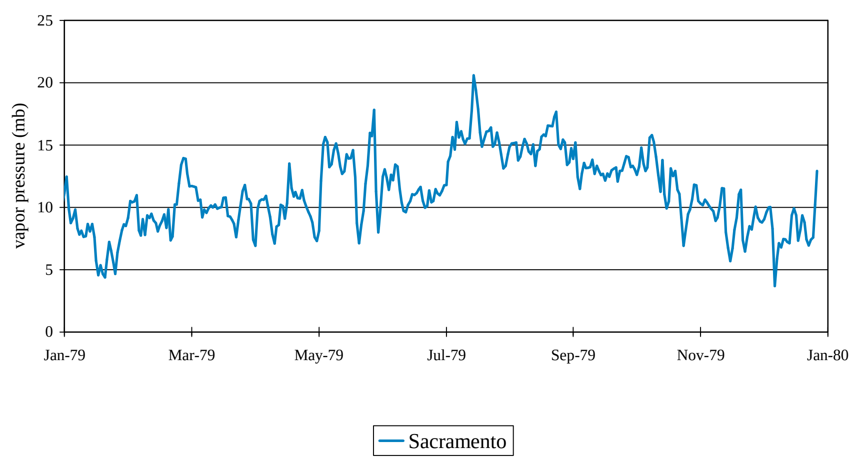
1979 Adjusted Wind Sacramento Site



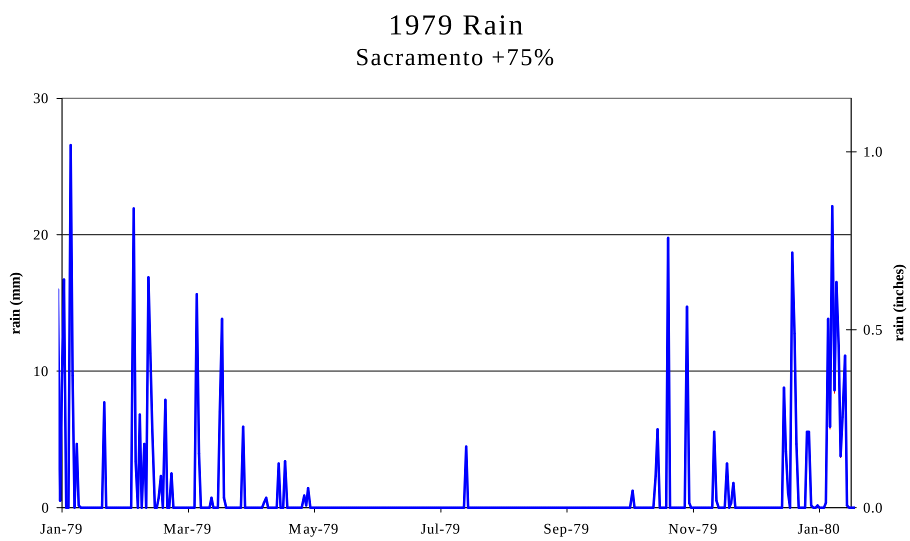
1979 Solar Radiation NCDC Sacramento Site -1.0%

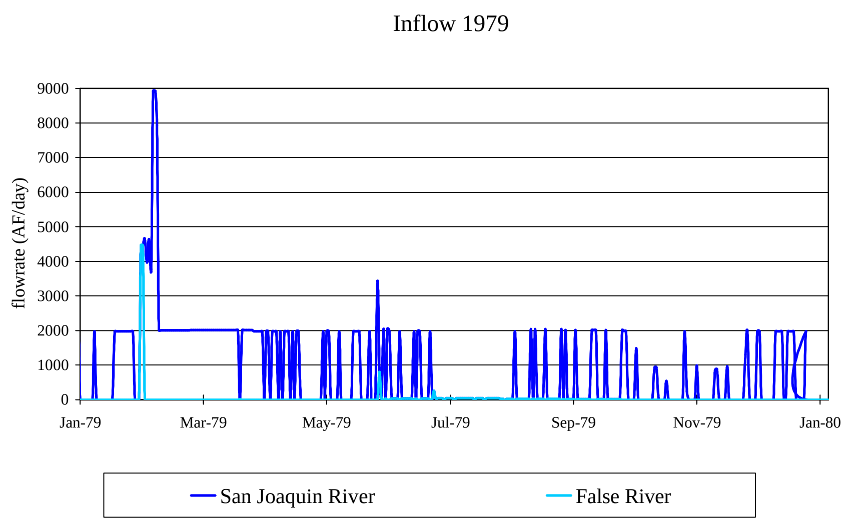


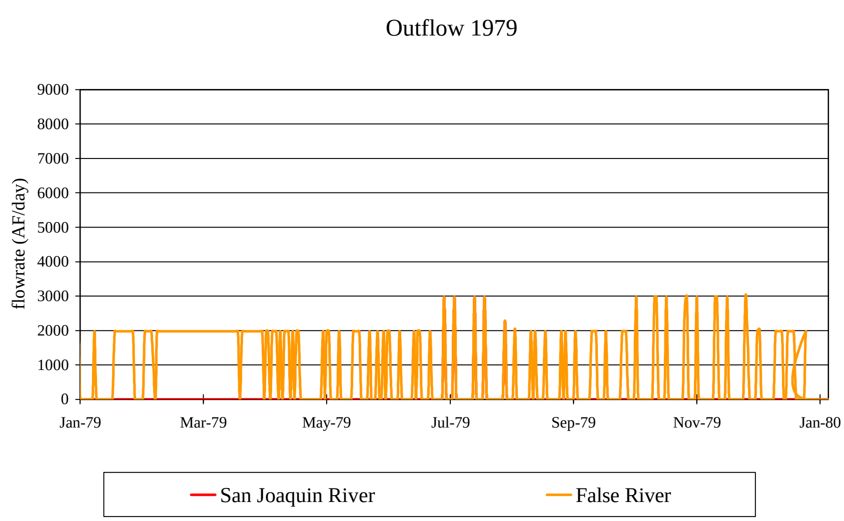
1979 Vapor Pressure NCDC Sacramento Site -5.0%



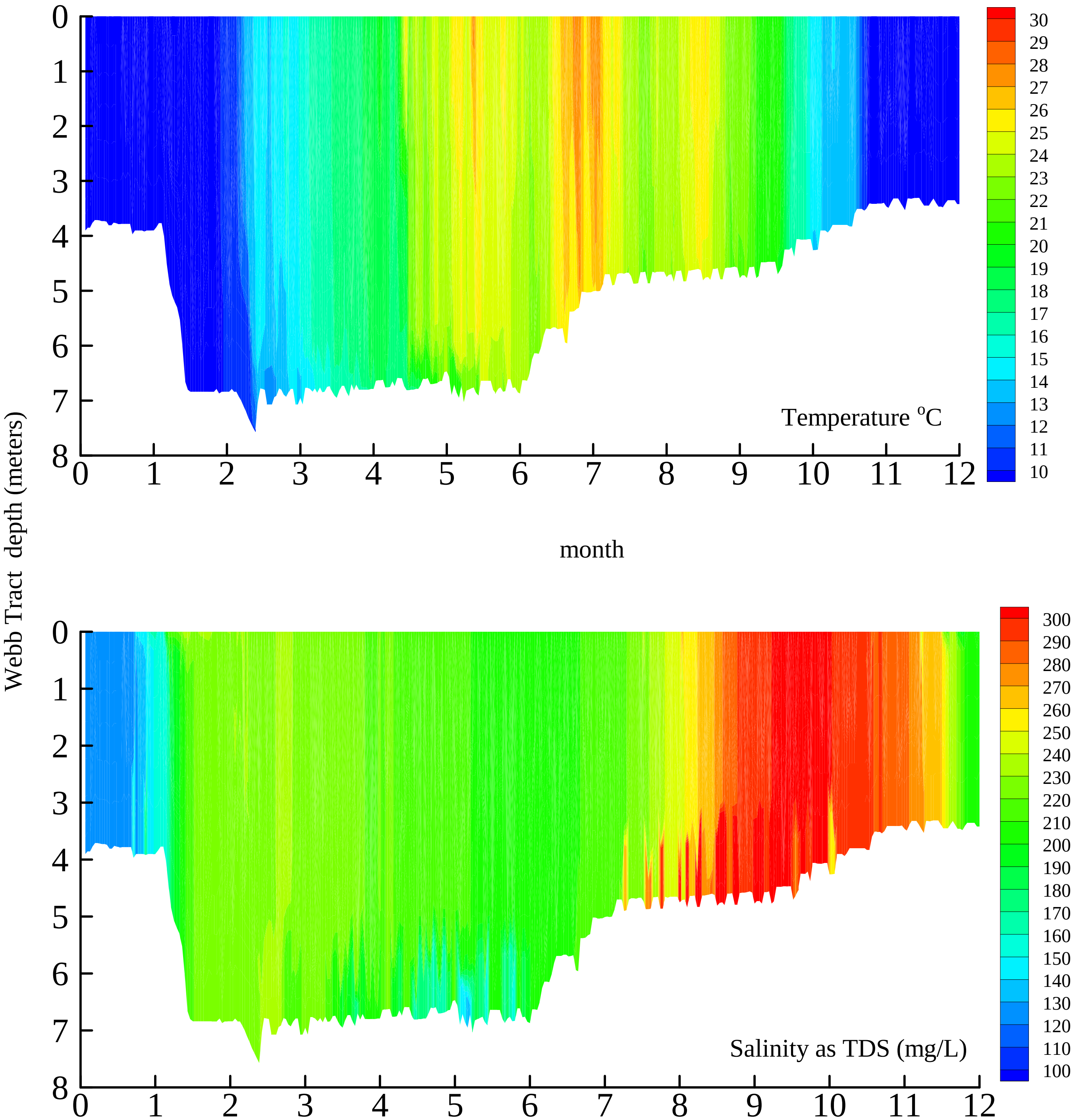
Webb Tract
1979 Flow



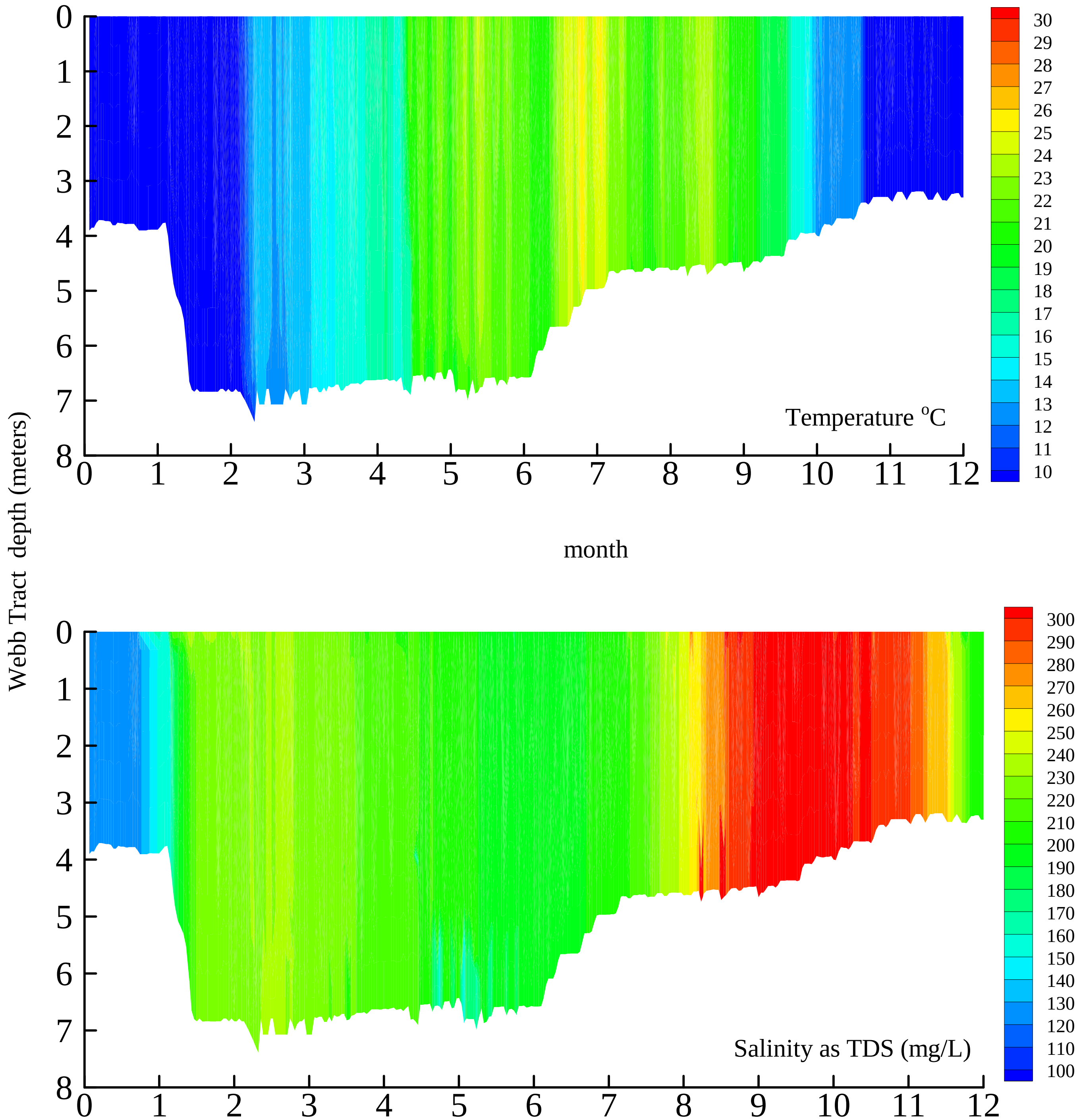




Webb Tract
1979 Low Wind Scenario DYRESM Profiles

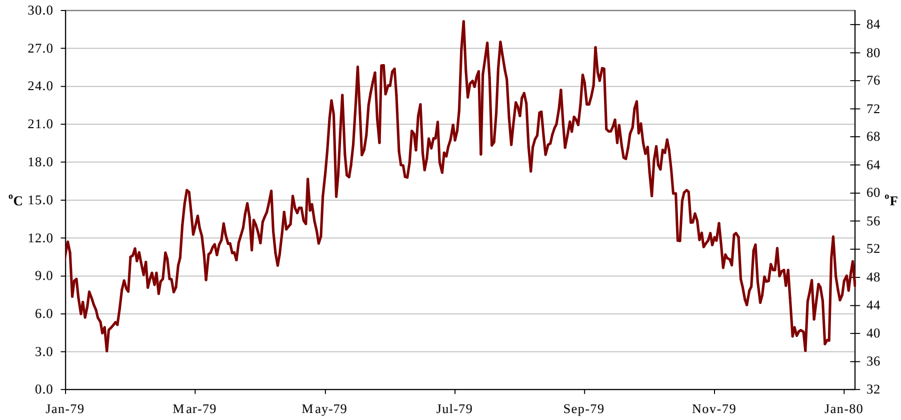


Webb Tract
1979 High Wind Scenario DYRESM Profiles

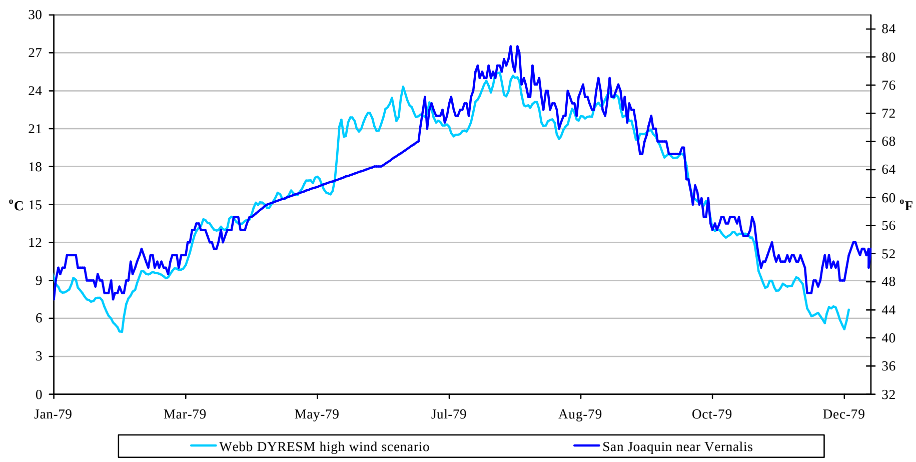


1979 Temperature Data

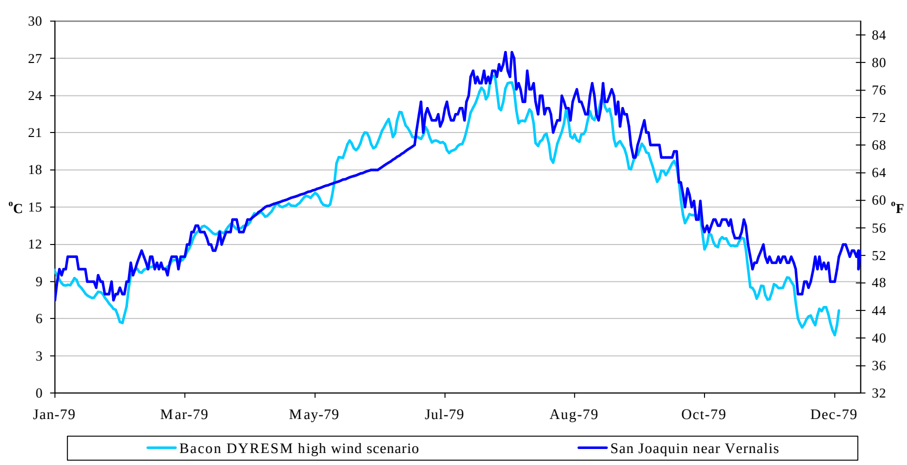
1979 Air Temperature
NCDC Sacramento Site -3.0%



1979 Webb Tract
Comparison of River to Simulated Reservoir Temperatures

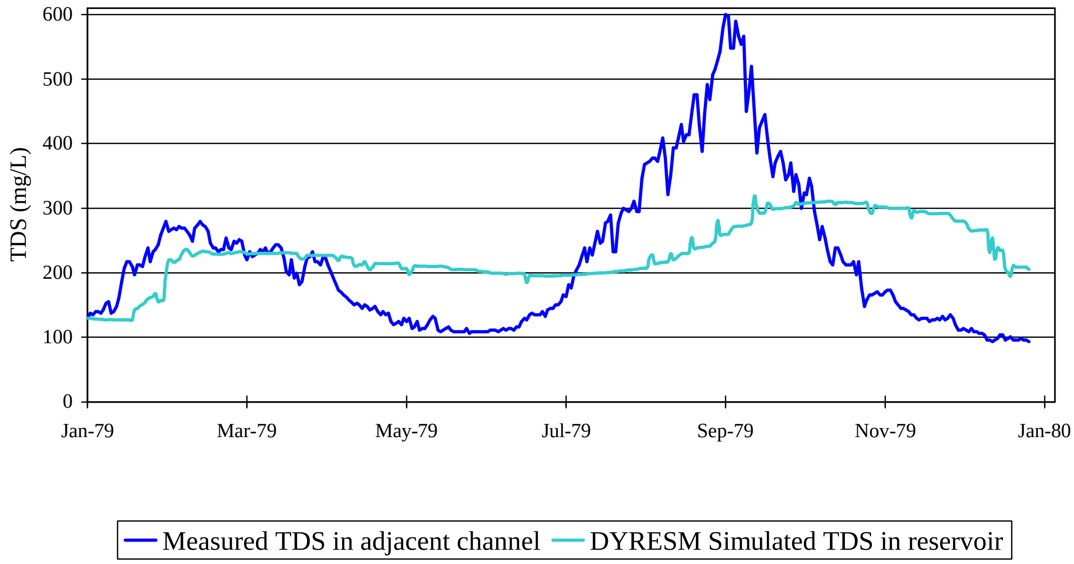


1979 Bacon Island
Comparison of River to Simulated Reservoir Temperatures

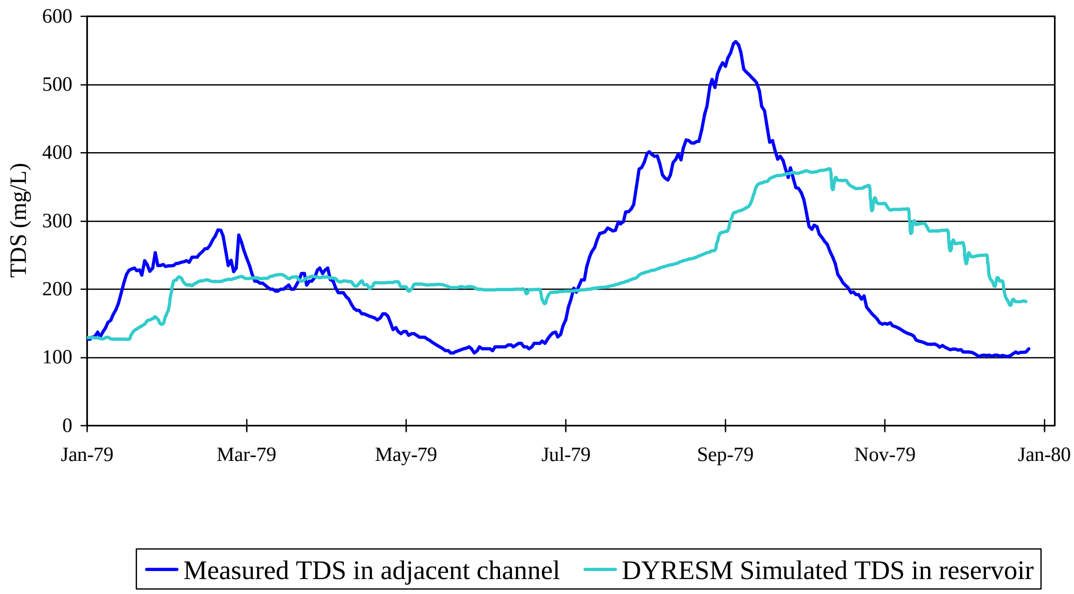


Salinity
1979 River and Reservoir

Webb Tract
Daily Average TDS

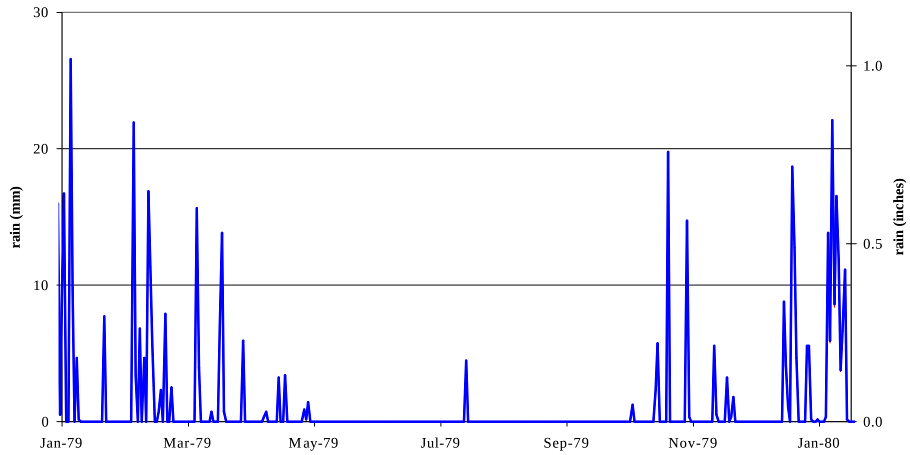


Bacon Island
Daily Average TDS

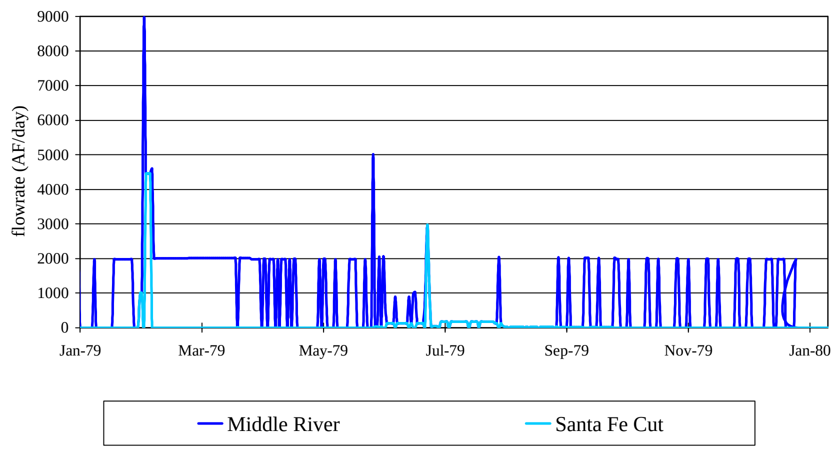


Bacon Island
1979 Flow

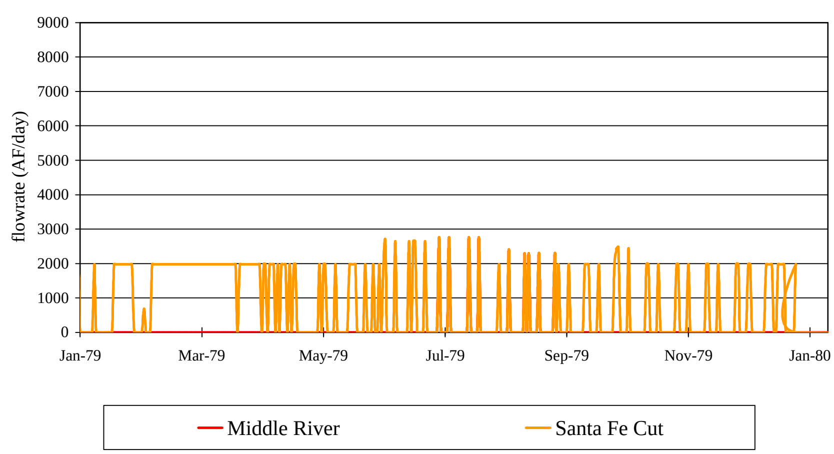
1979 Rain
Sacramento +75%



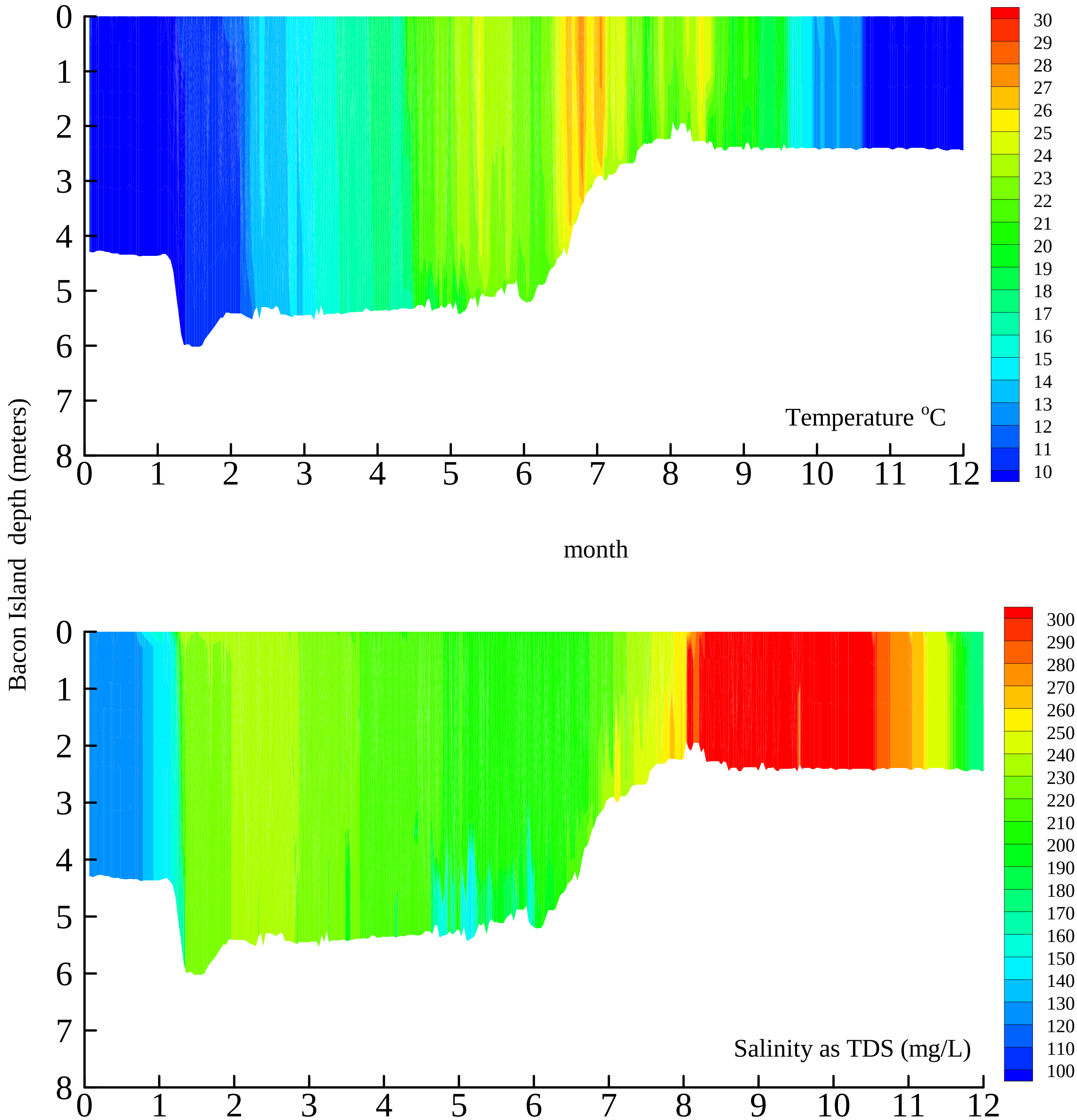
Inflow 1979



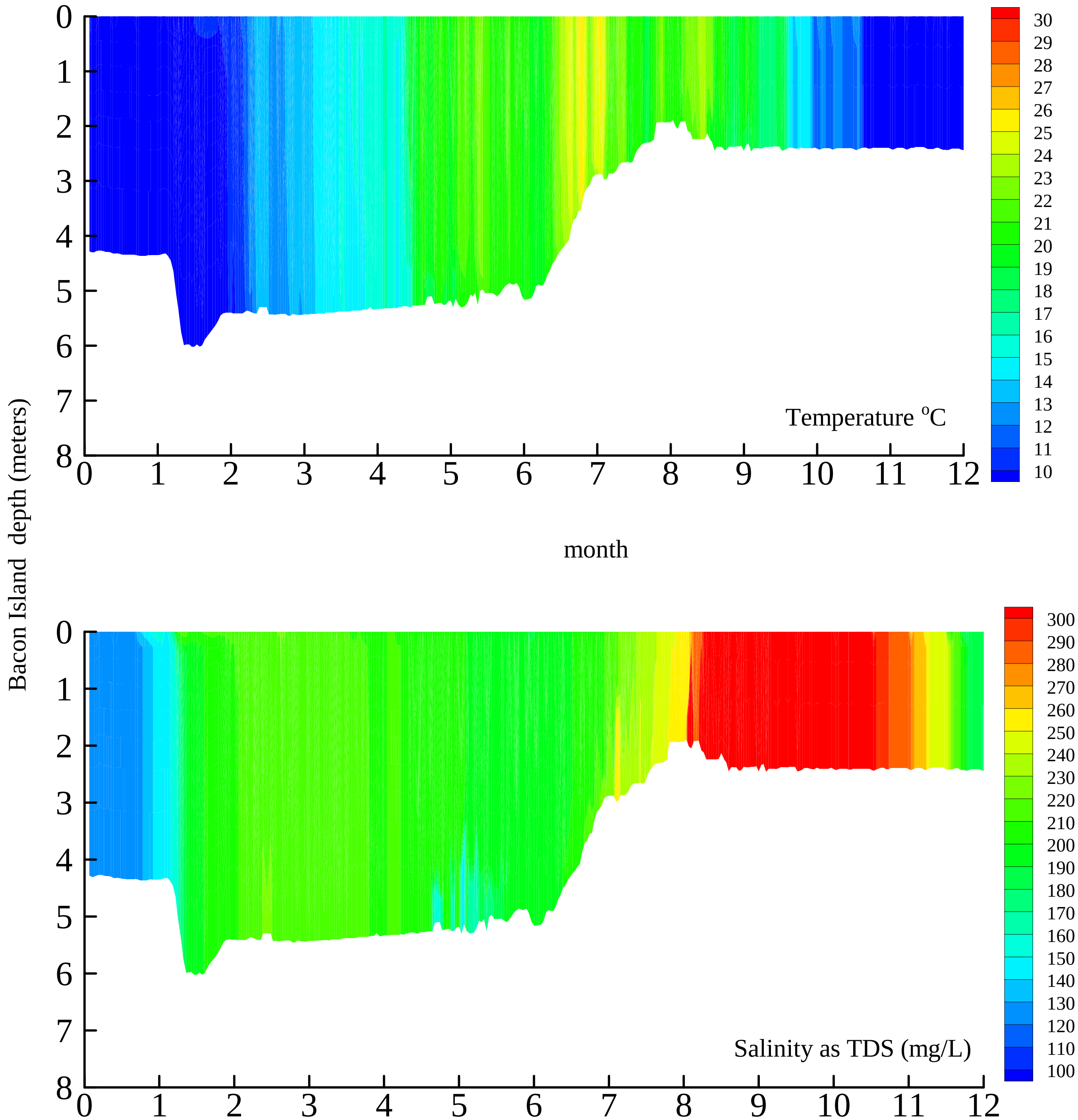
Outflow 1979



Bacon Island
1979 Low Wind Scenario DYRESM Profiles

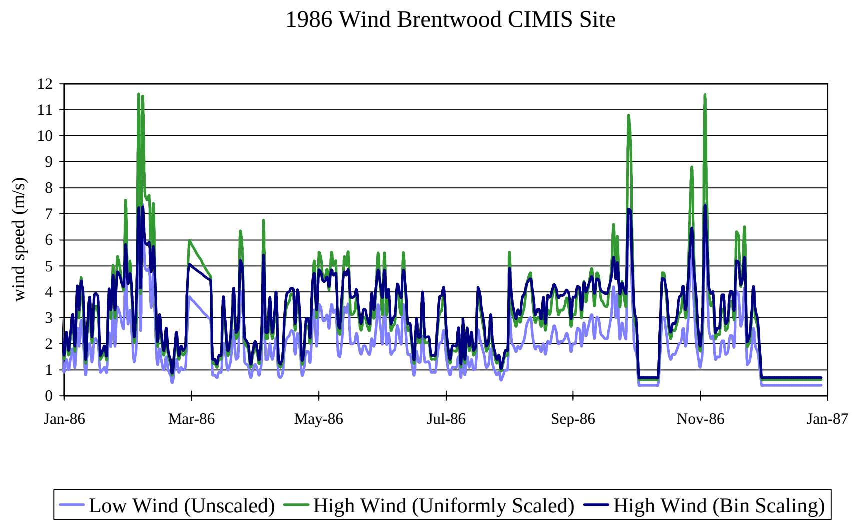


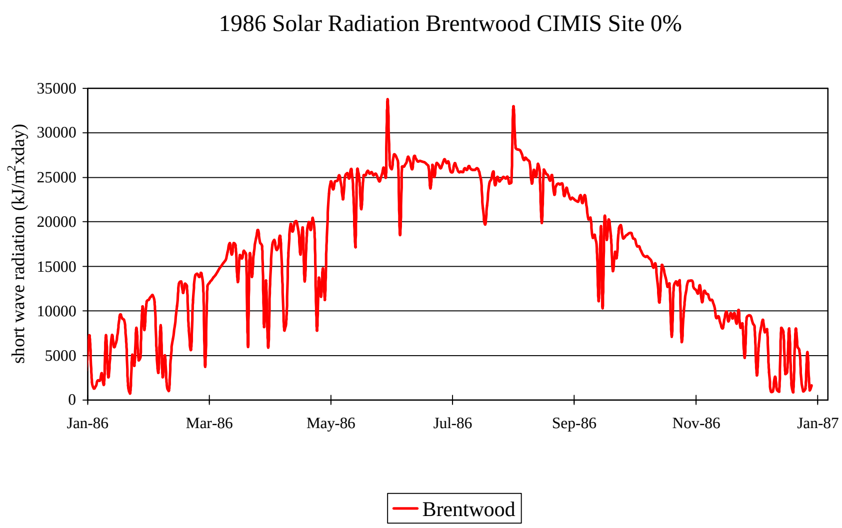
Bacon Island
1979 High Wind Scenario DYRESM Profiles

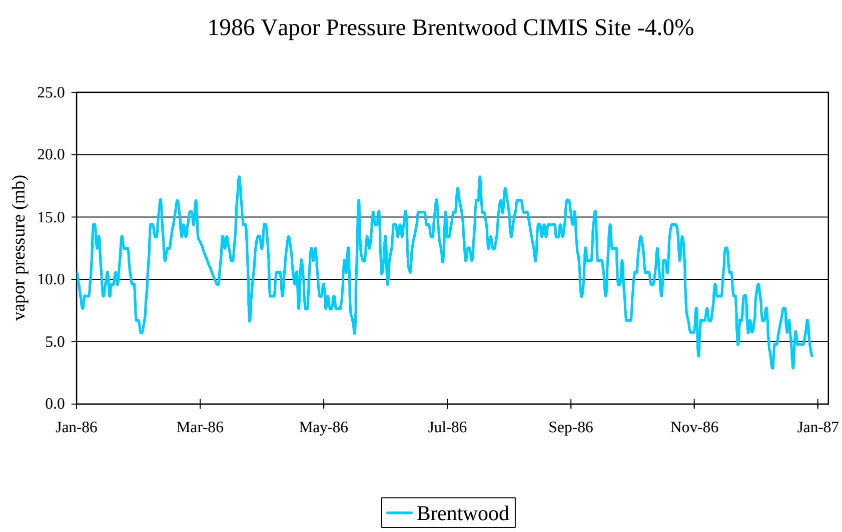


Appendix C
1986 (Wet Year) Simulation

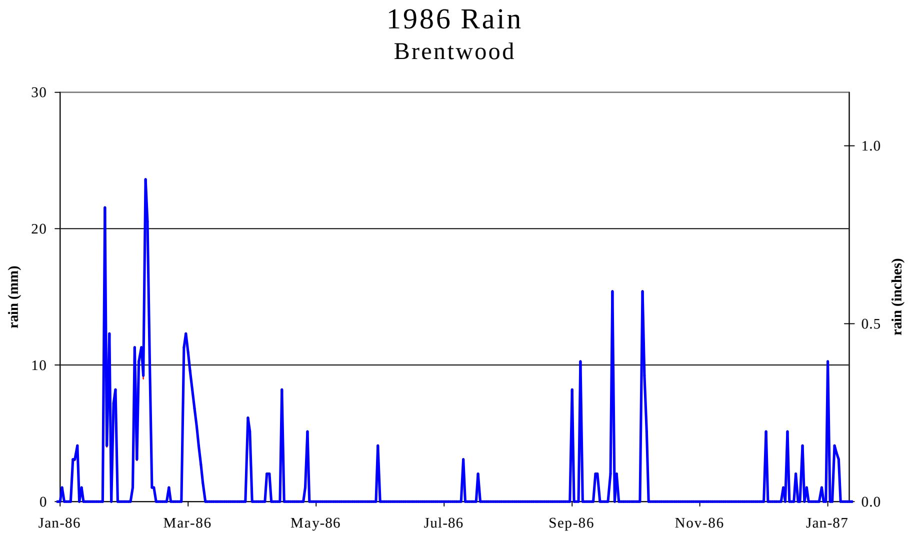
DYRESM
1986 Meteorological Data

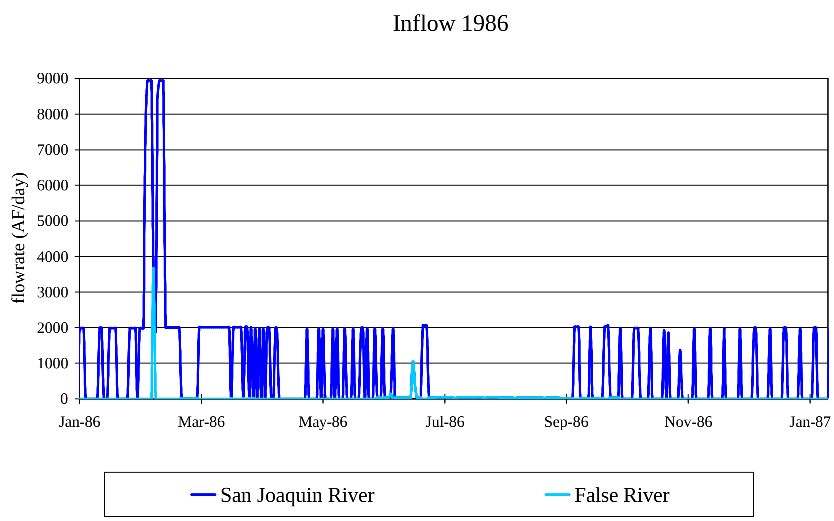


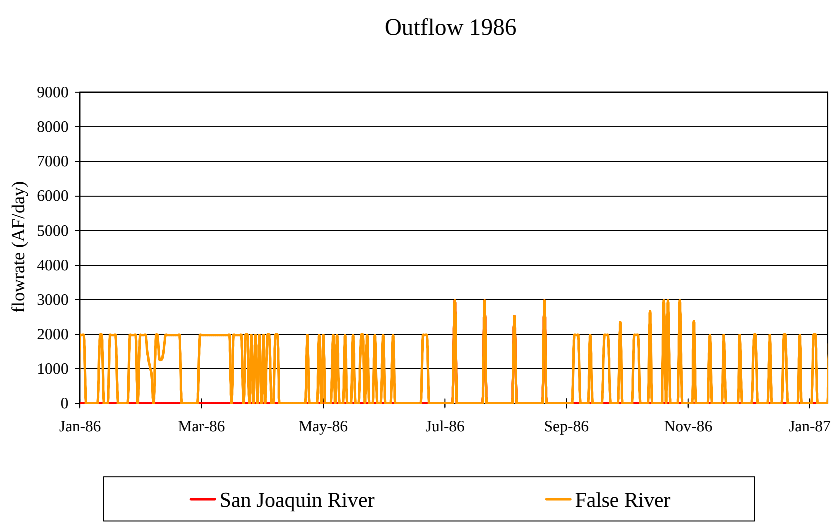




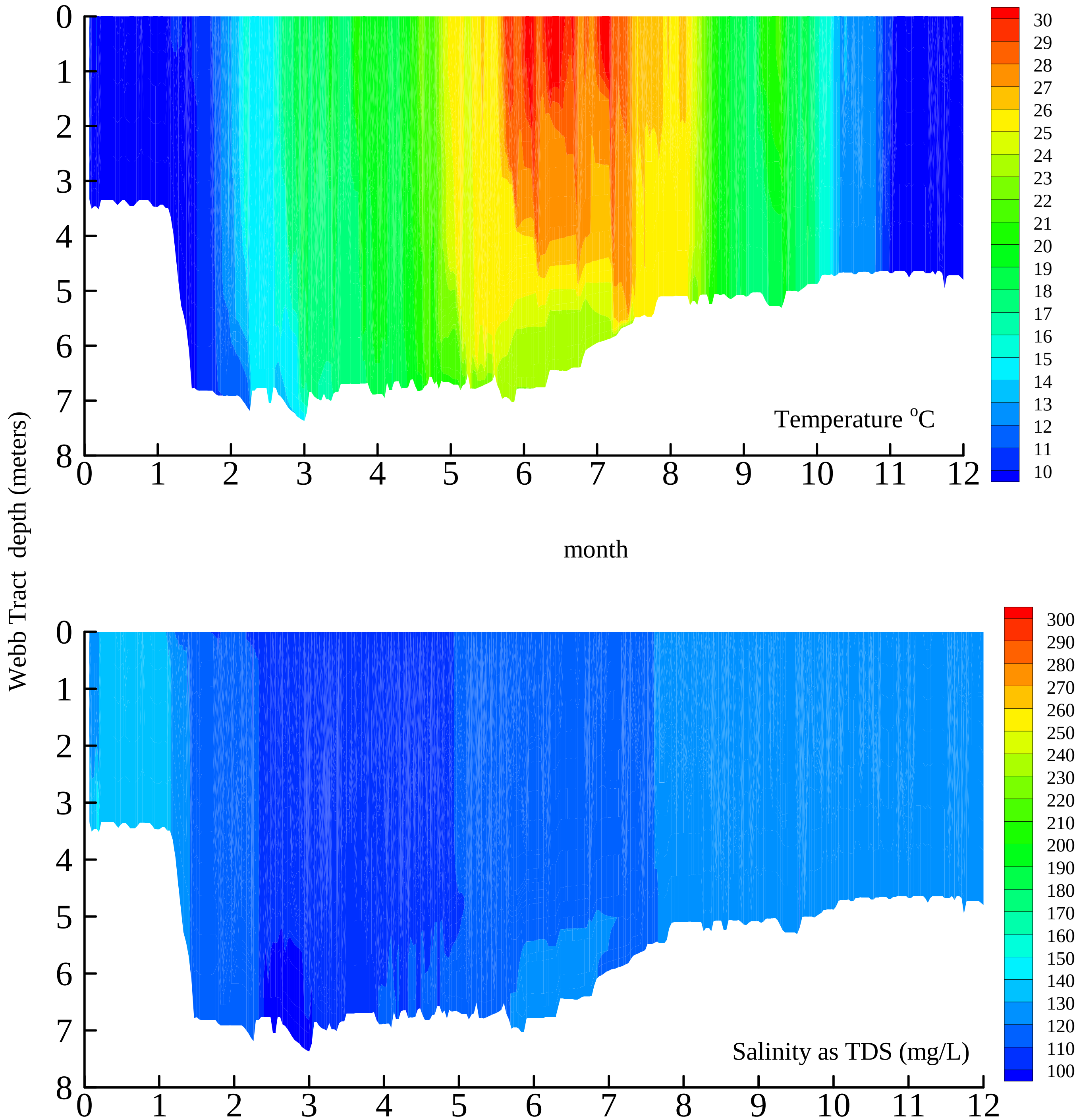
Webb Tract
1986 Flow



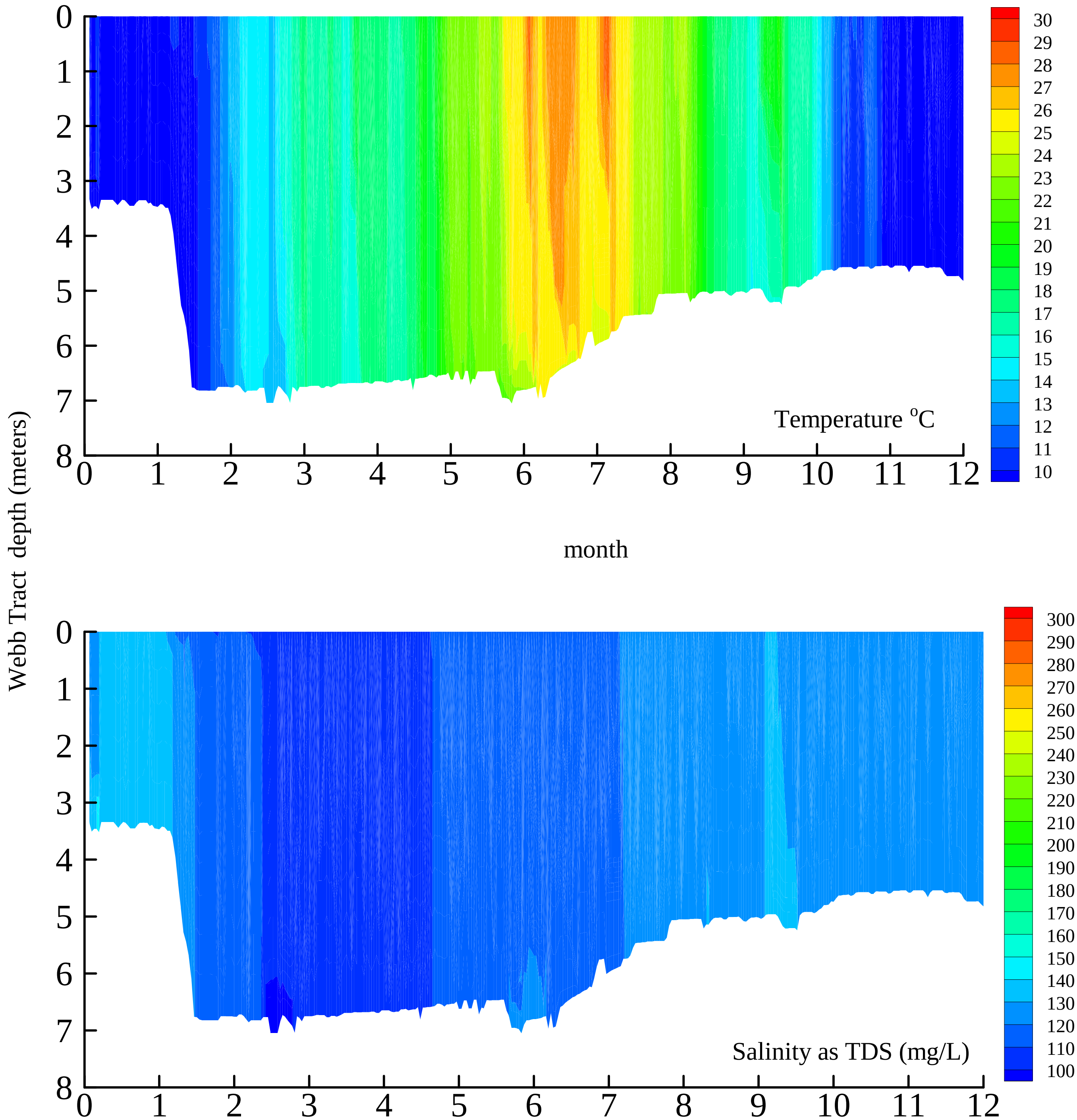




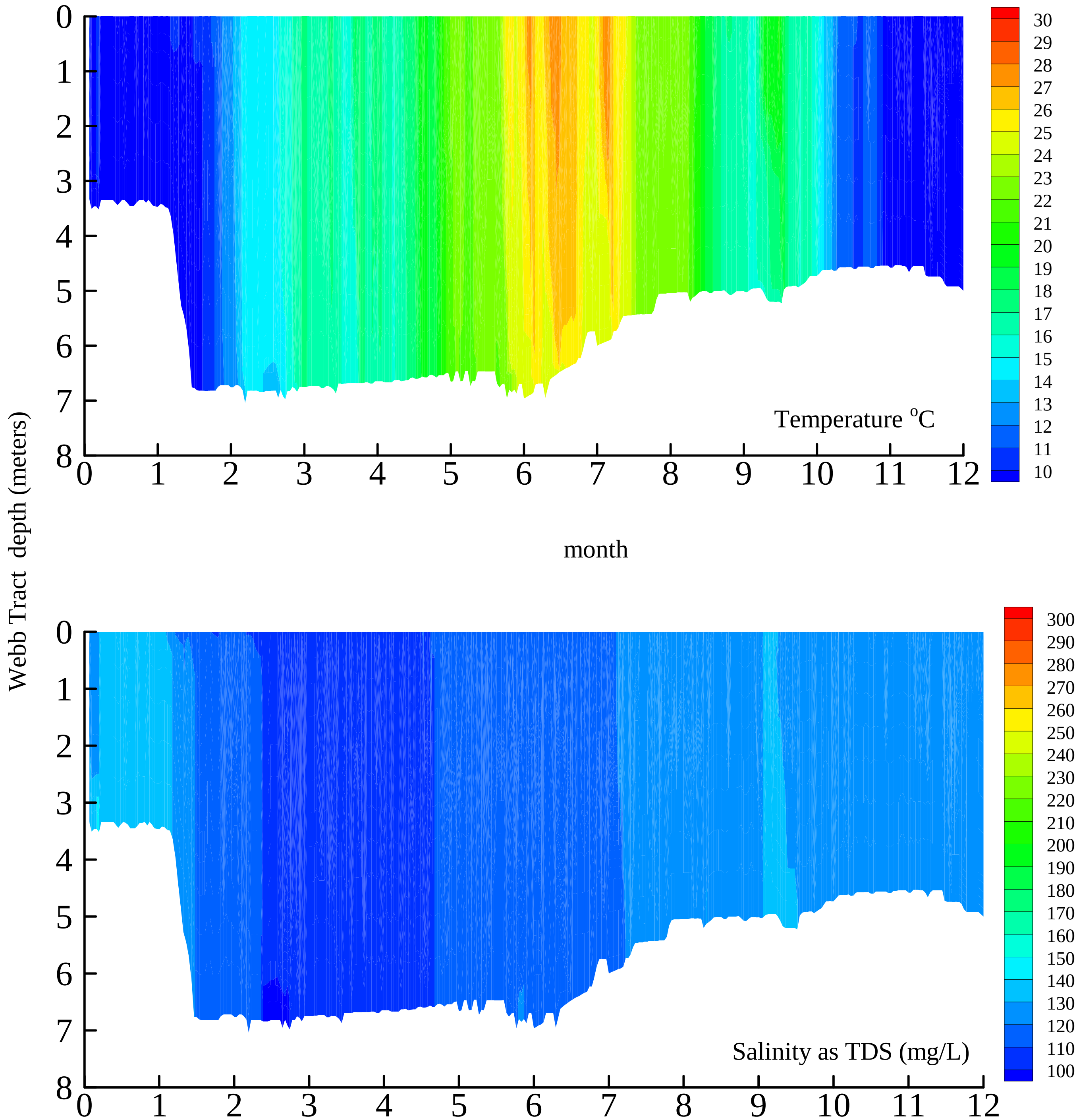
Webb Tract
1986 Low Wind DYRESM Profiles



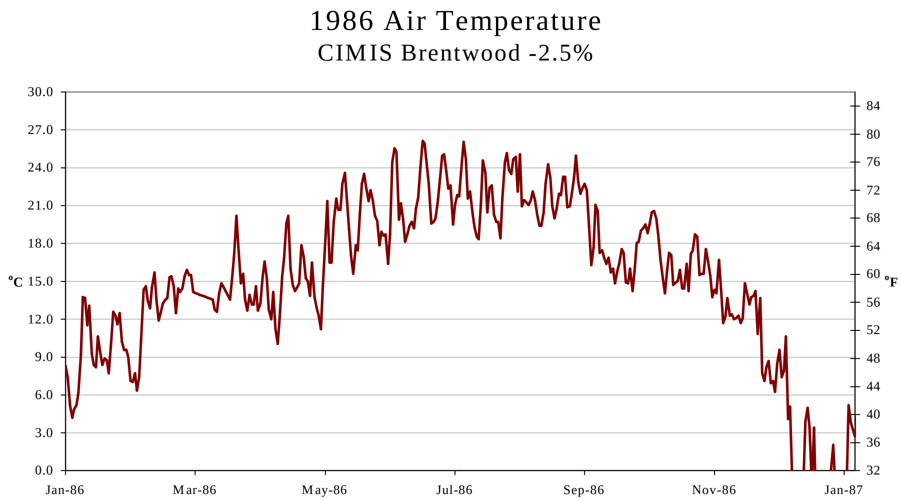
Webb Tract
1986 High (Scaled Uniformly) DYRESM Profiles

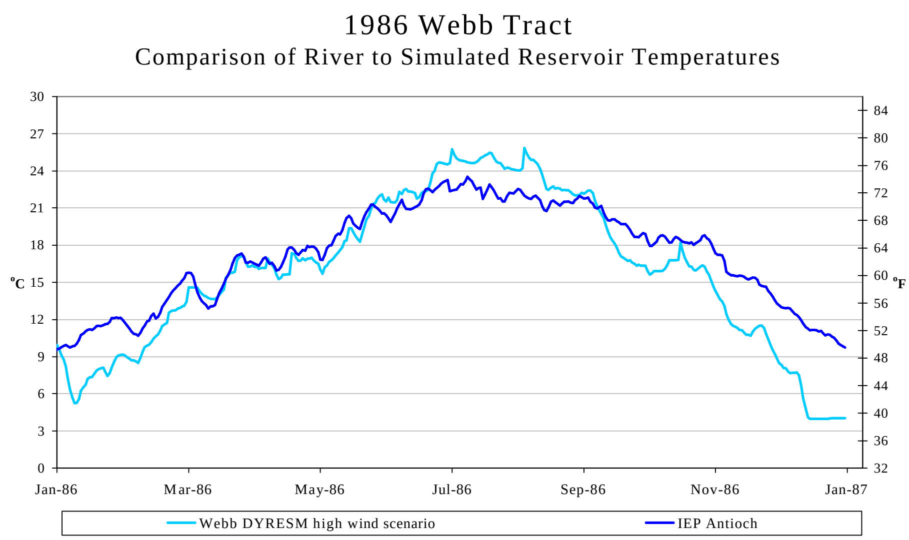


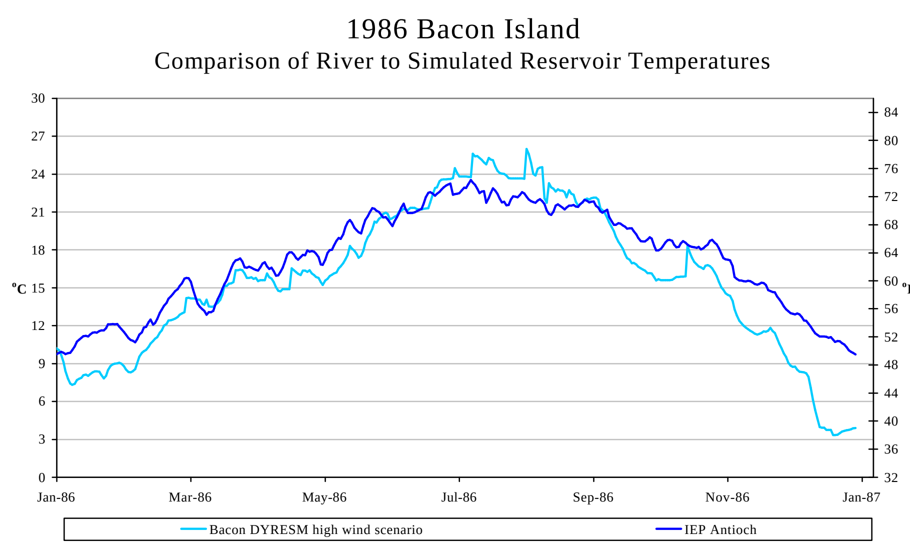
Webb Tract
1986 High Wind (Bin Scaling Approach) DYRESM



1986 Temperature Data



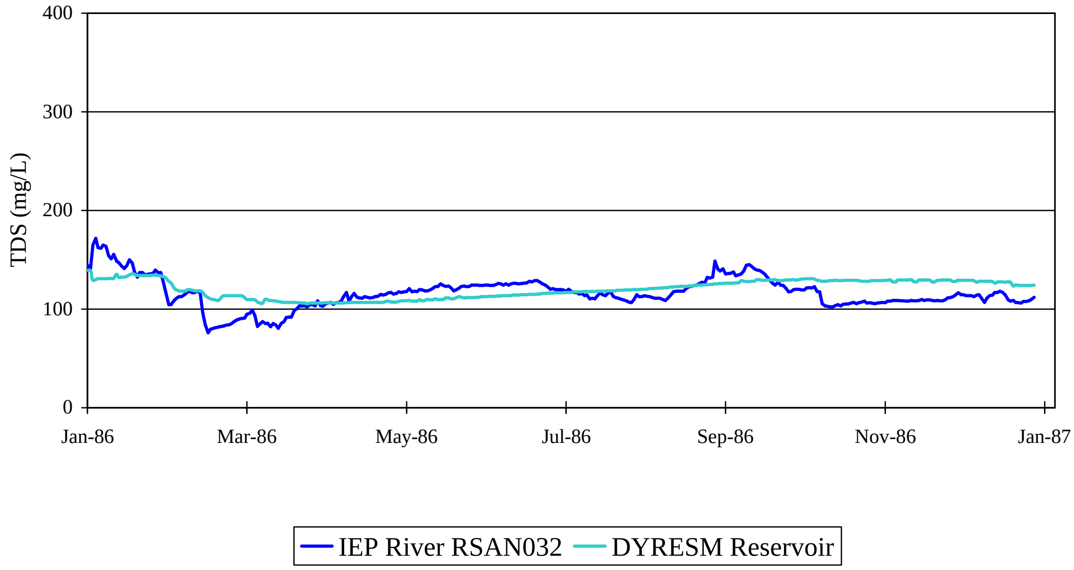




Salinity
1986 River and Reservoir

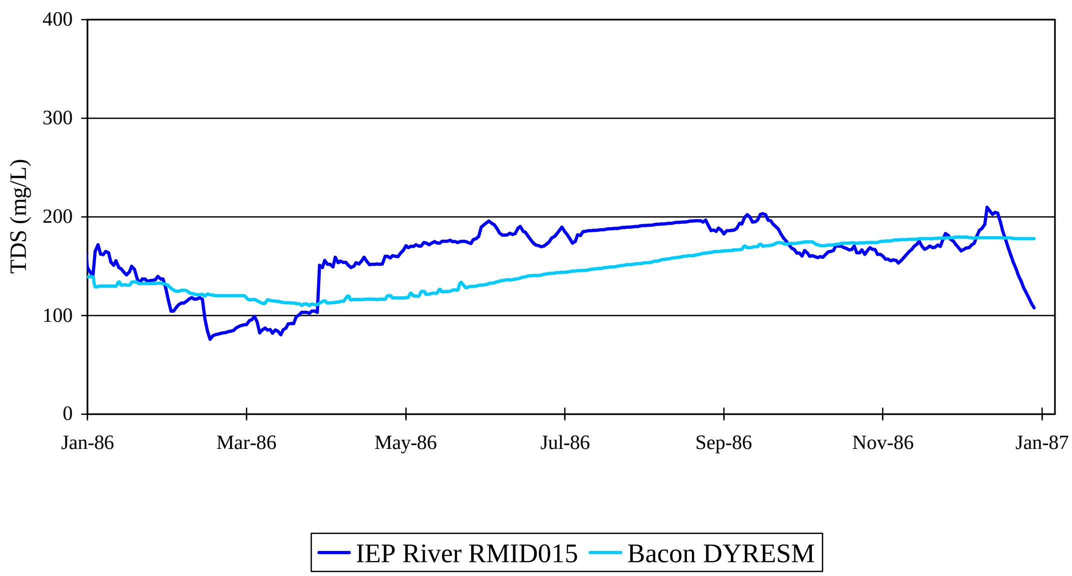
Webb Tract

Daily TDS Measurements wet year



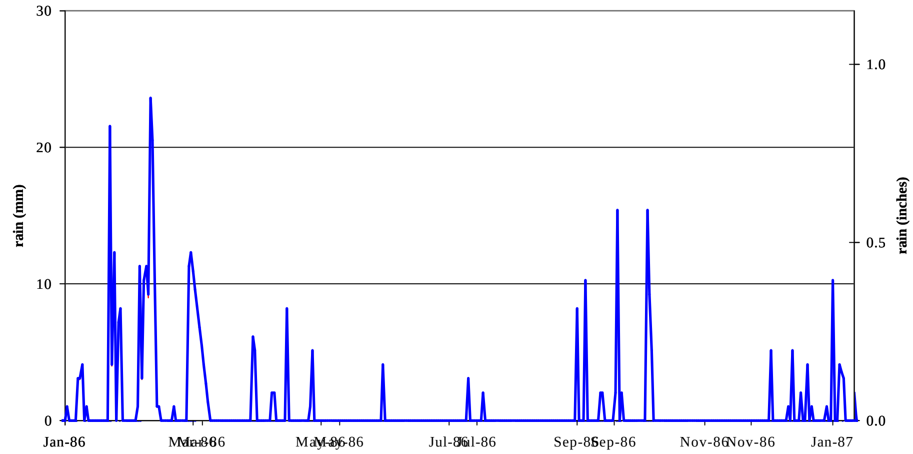
Bacon Island

Daily TDS Measurements wet year January - March (Source RSAN032)

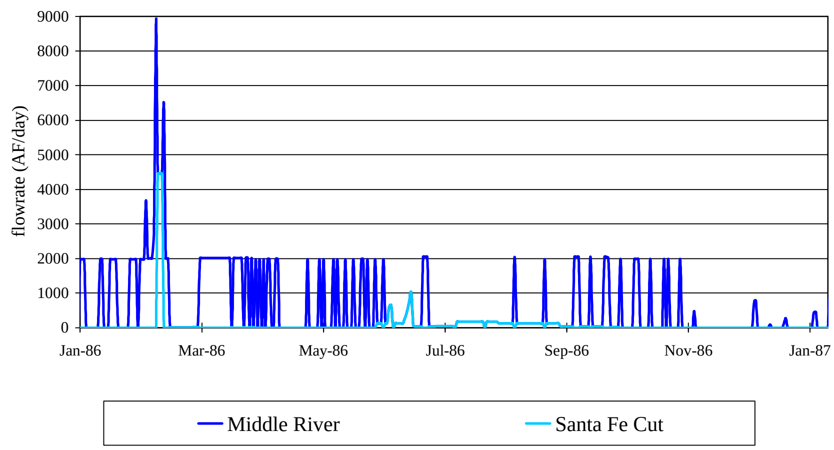


Bacon Island
1986 Flow

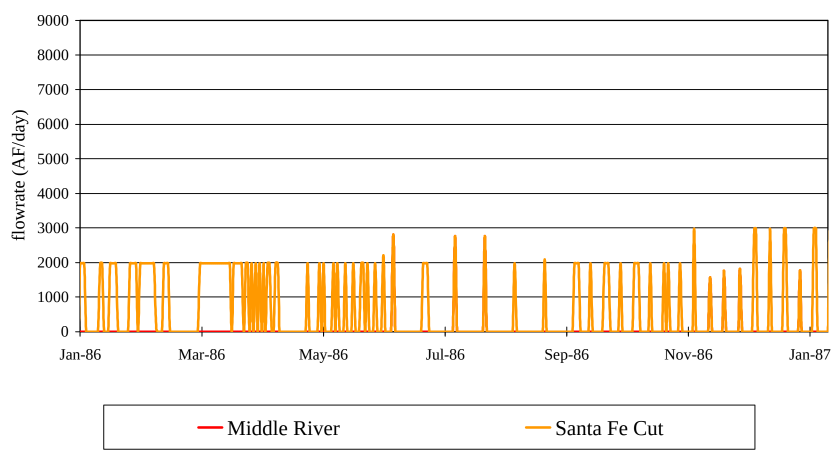
1986 Rain
Brentwood



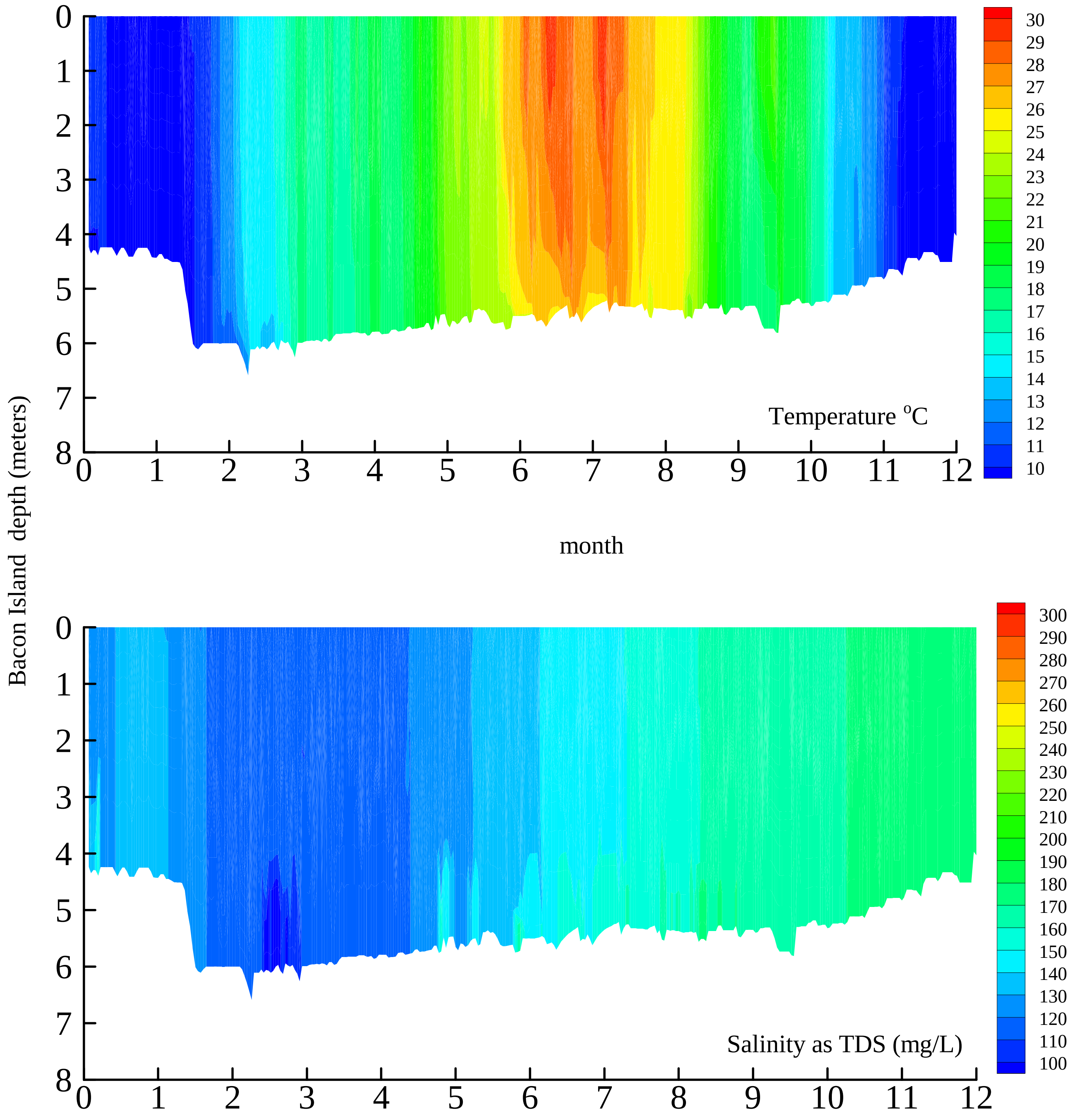
Inflow 1986



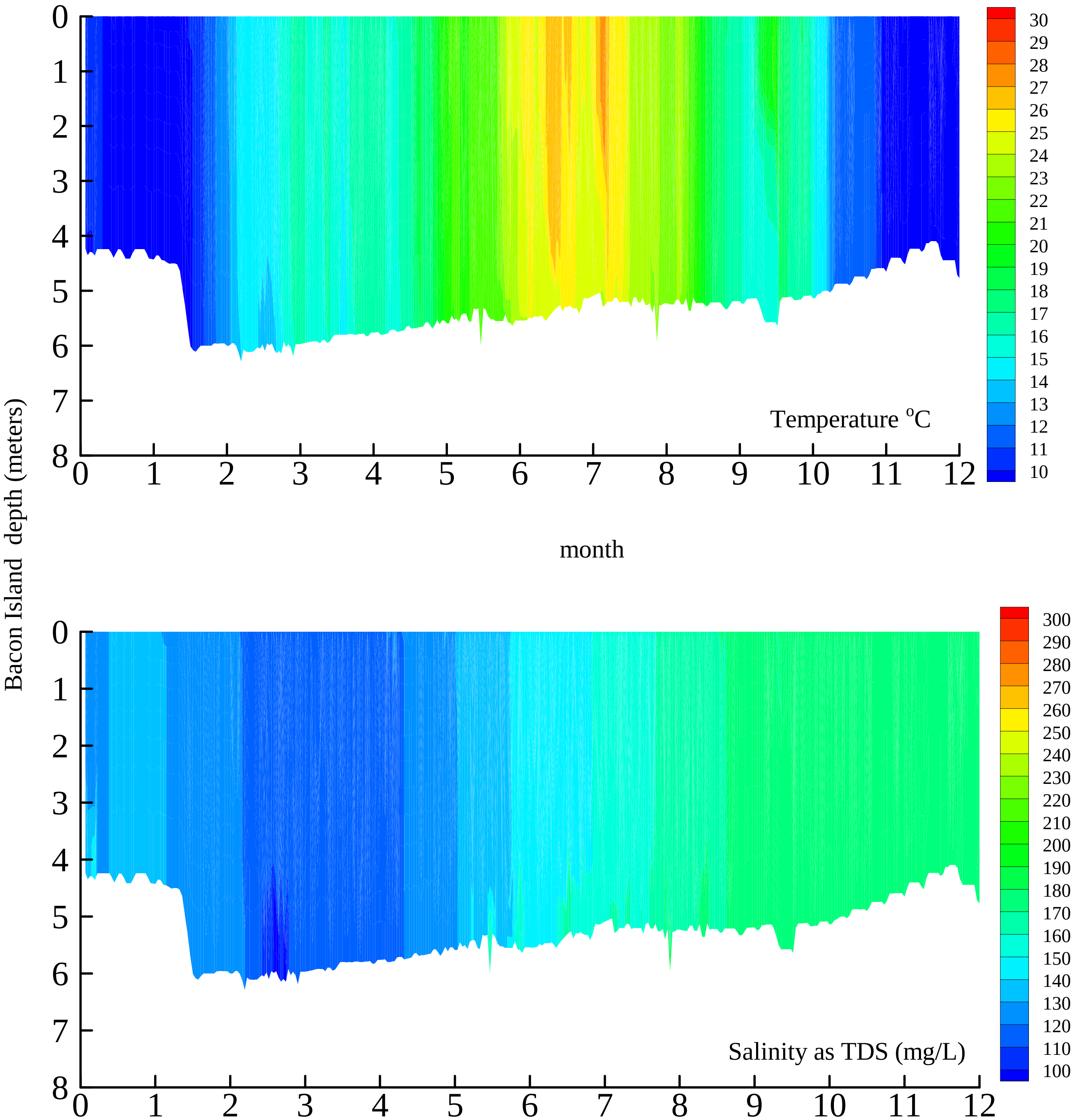
Outflow 1986



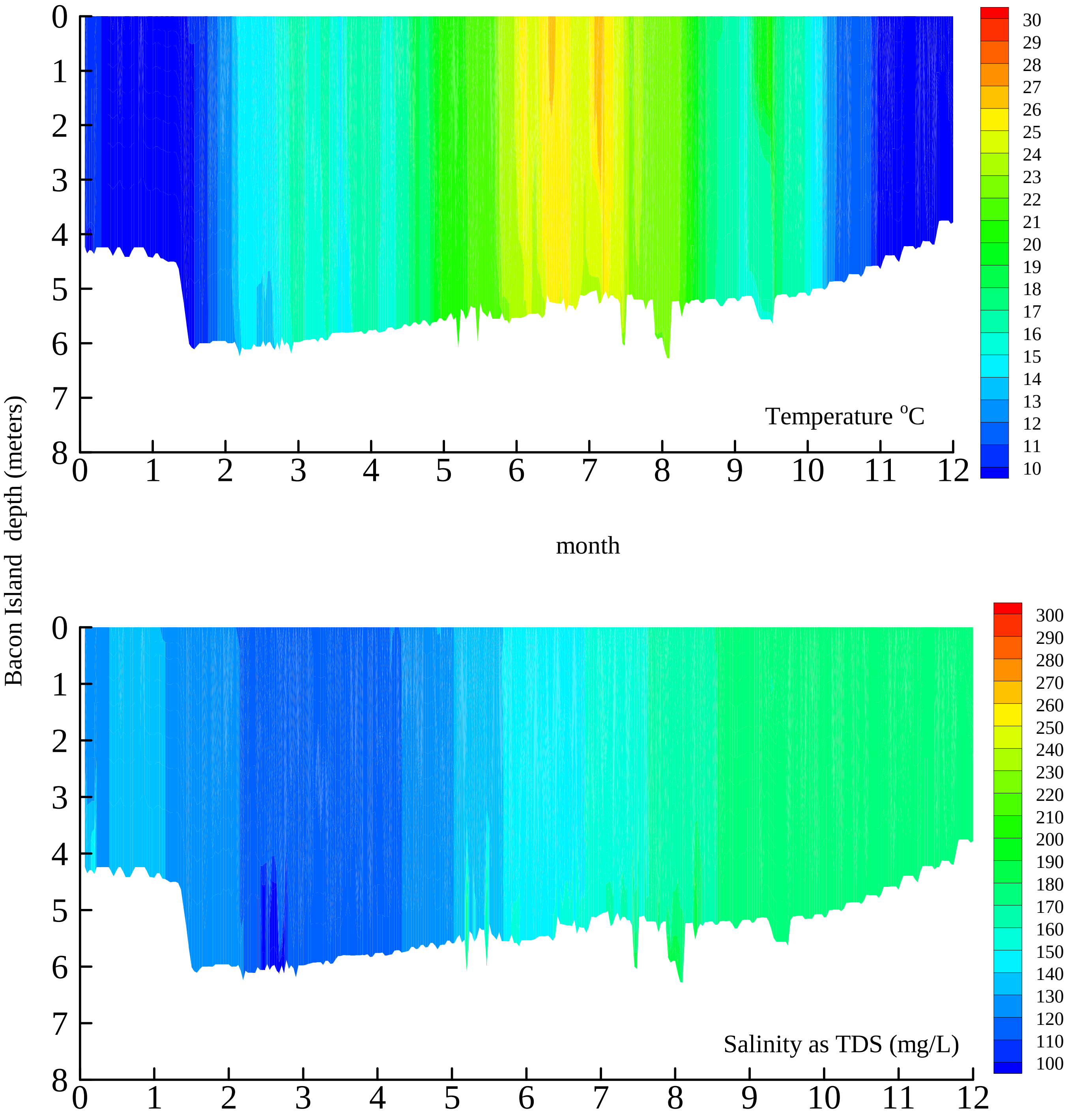
Bacon Island
1986 Low Wind DYRESM Profiles



Bacon Island
1986 High (Scaled Uniformly) DYRESM Profiles

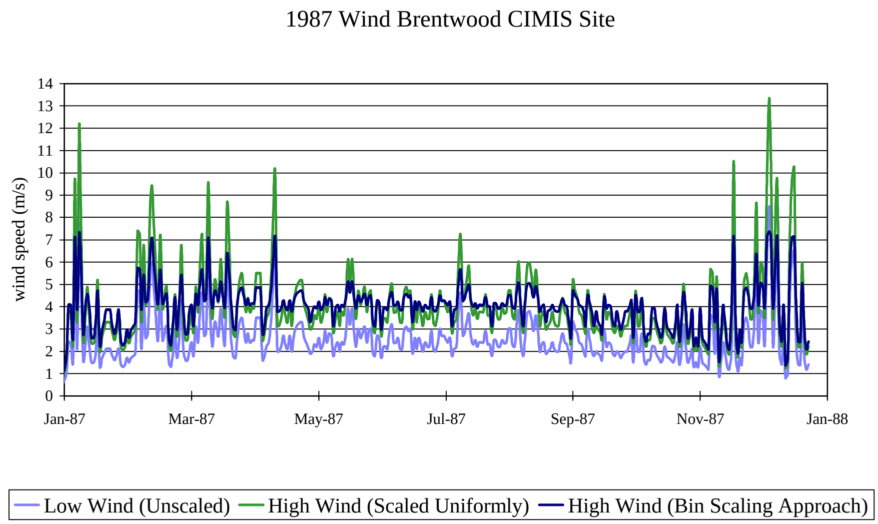


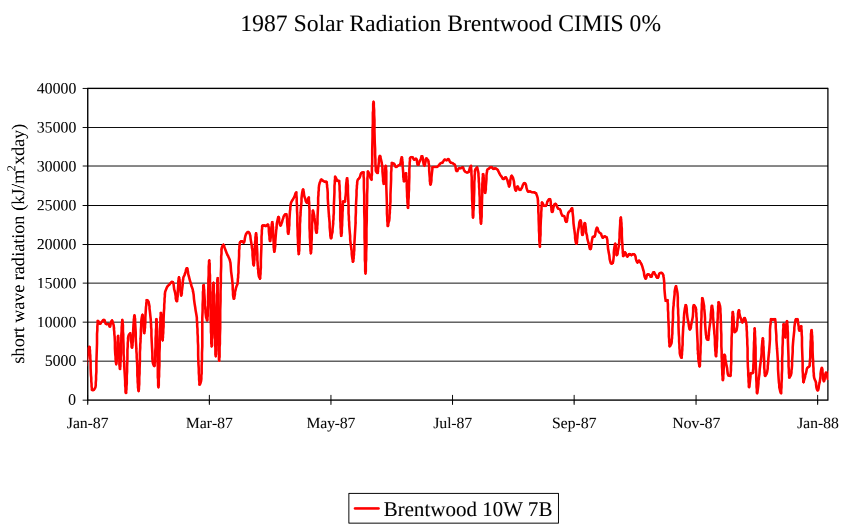
Bacon Island
1986 High Wind (Bin Scaling Approach) DYRESM

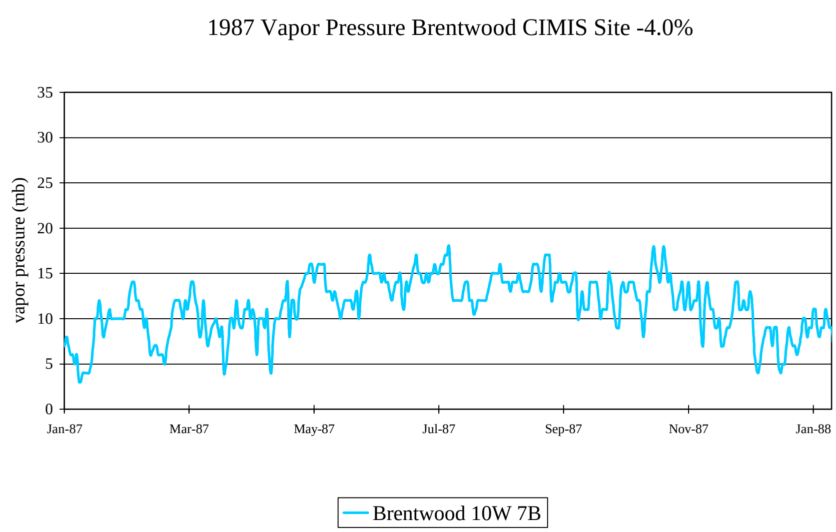


Appendix D
1987 (Dry Year) Simulation

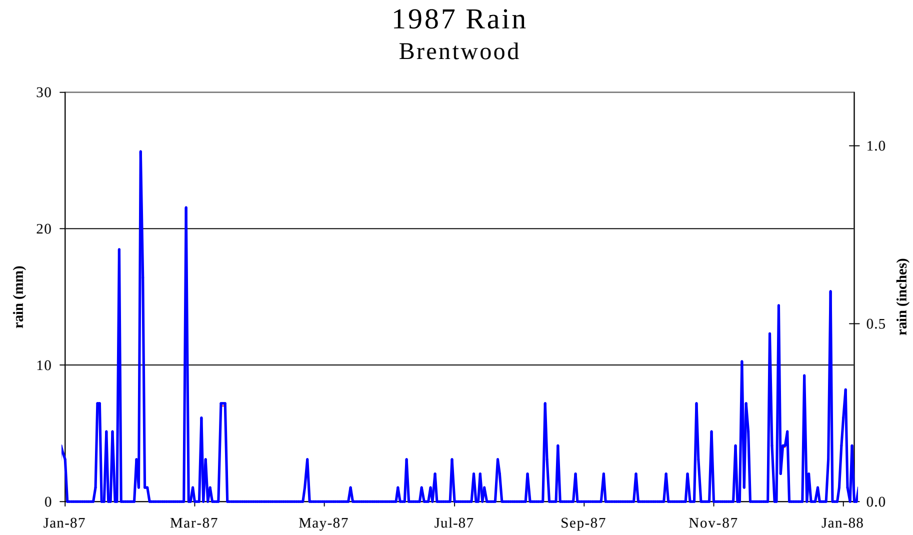
DYRESM
1987 Meteorological Data

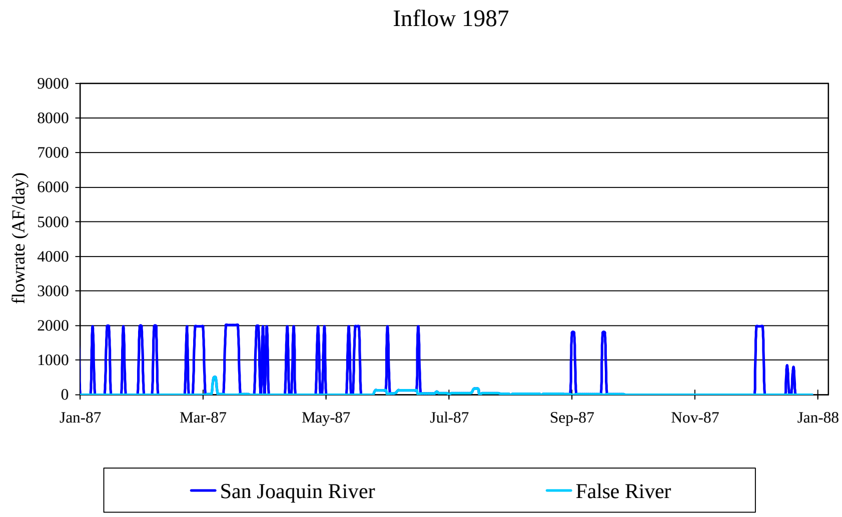


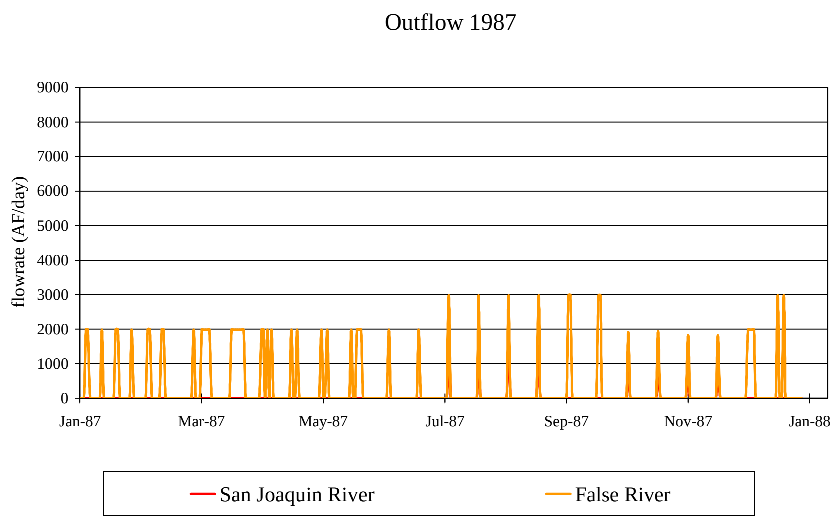




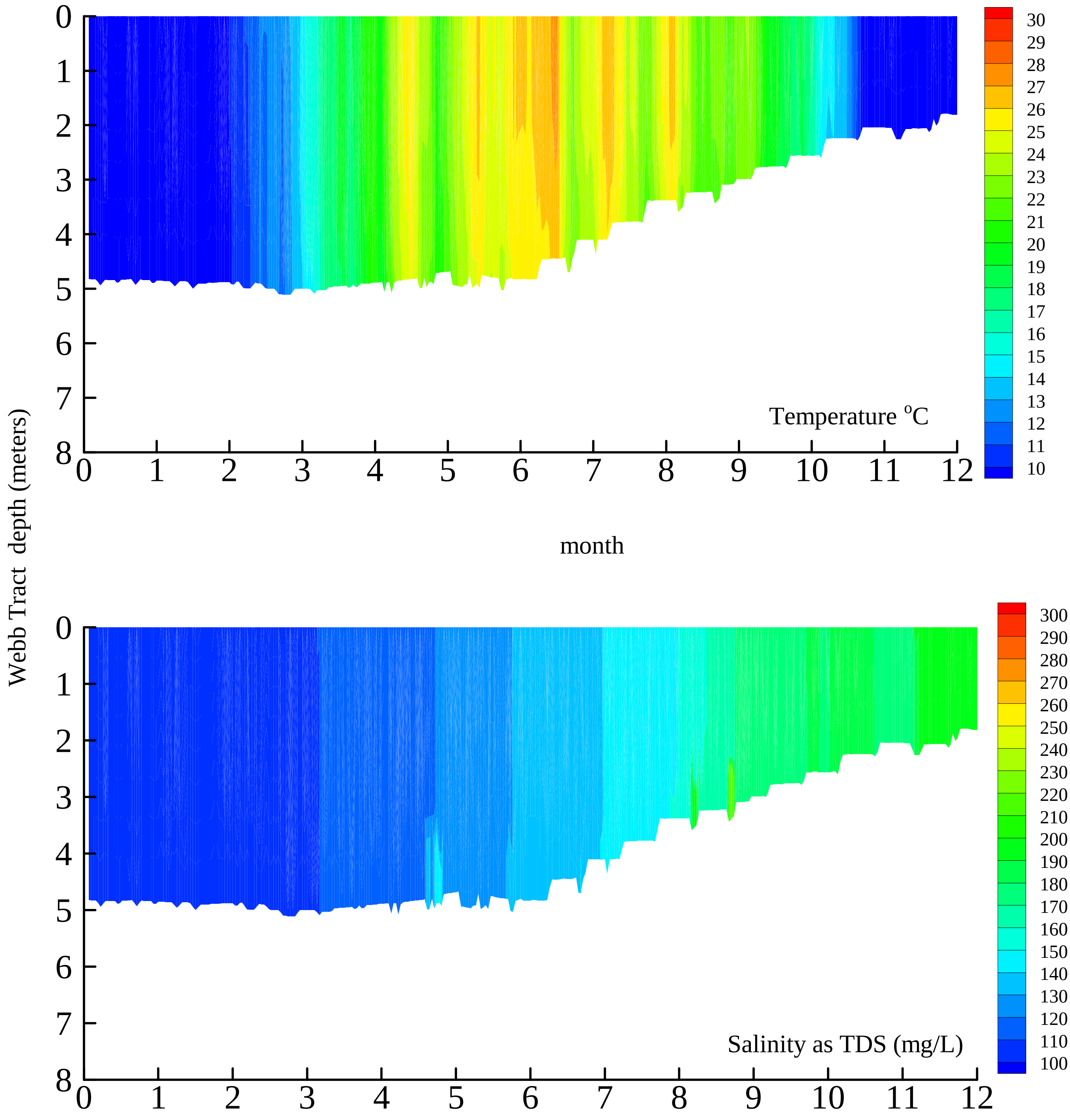
Webb Tract
1987 Flow



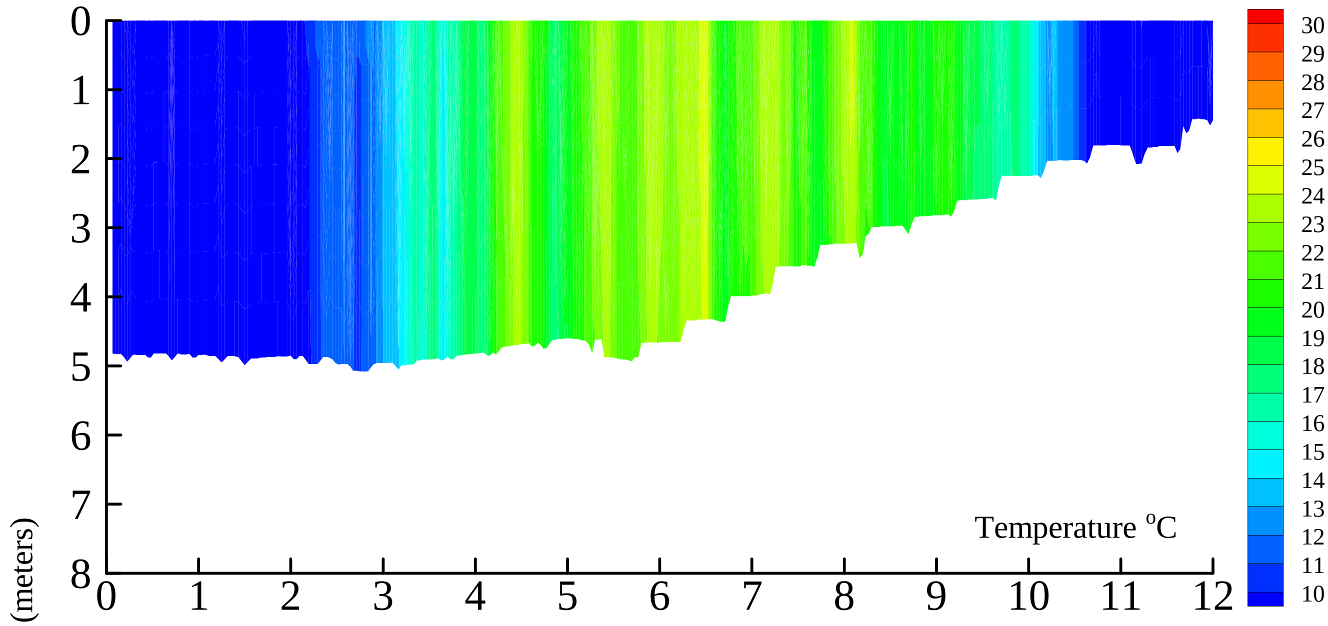


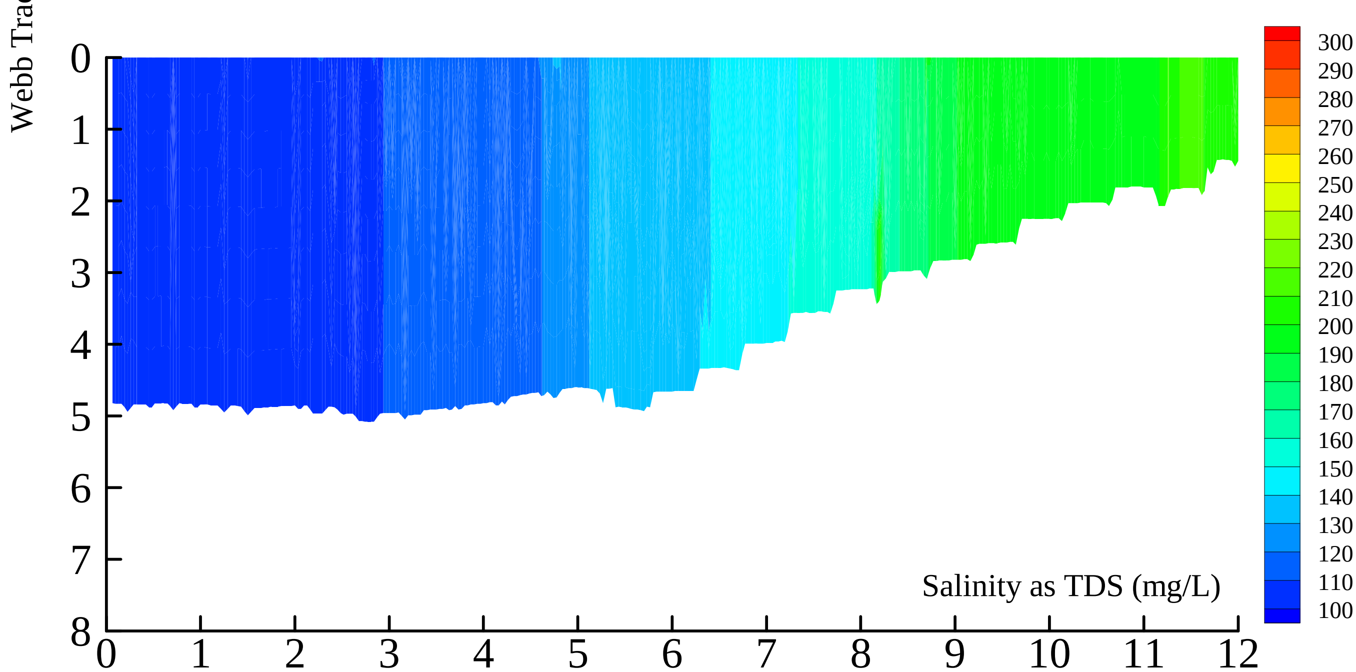


Webb Tract
1987 Low Wind Brentwood DYRESM Profiles

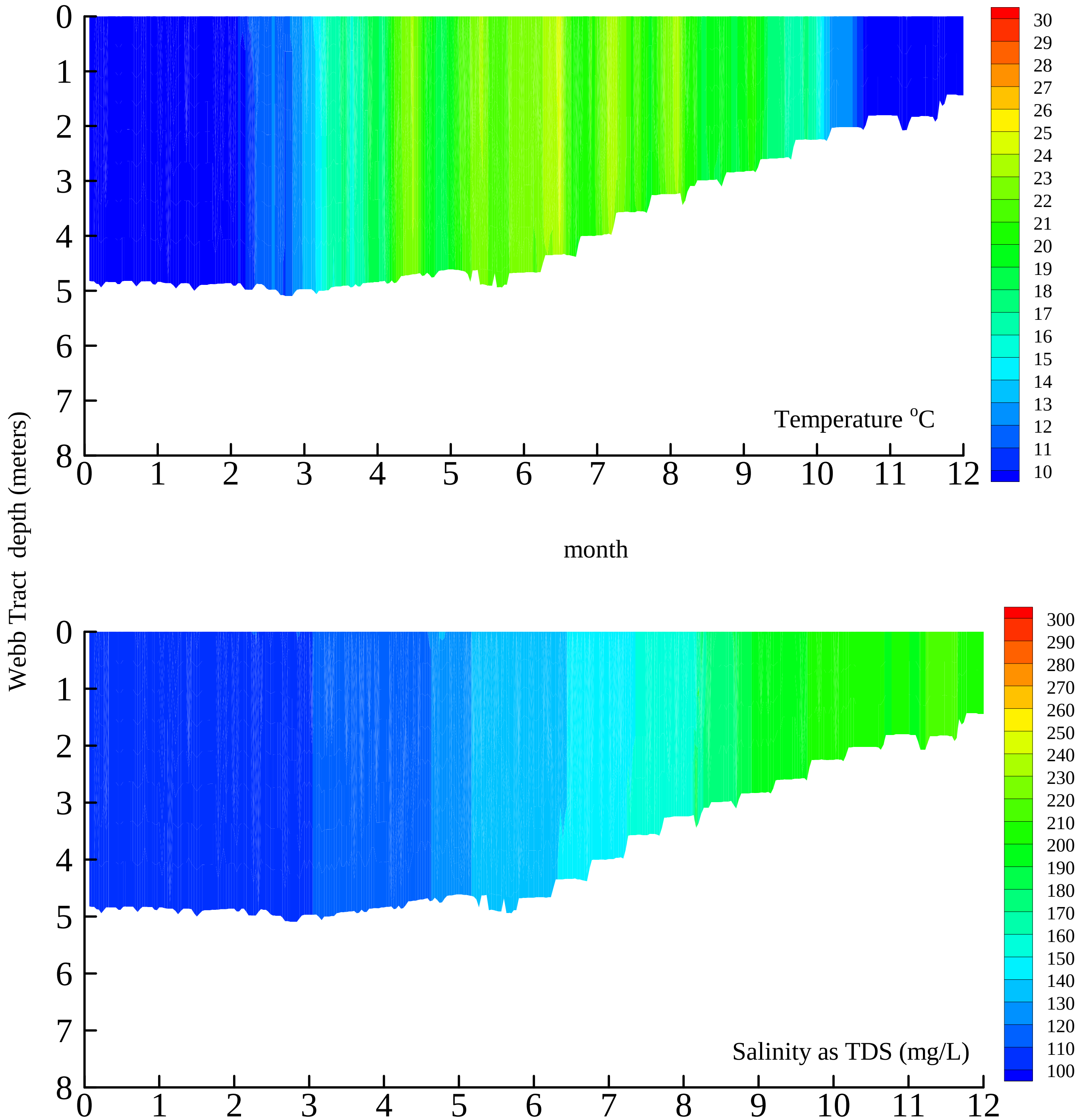


Webb Tract
1987 High Wind (Uniform Scaling Approach) DYRESM Profiles

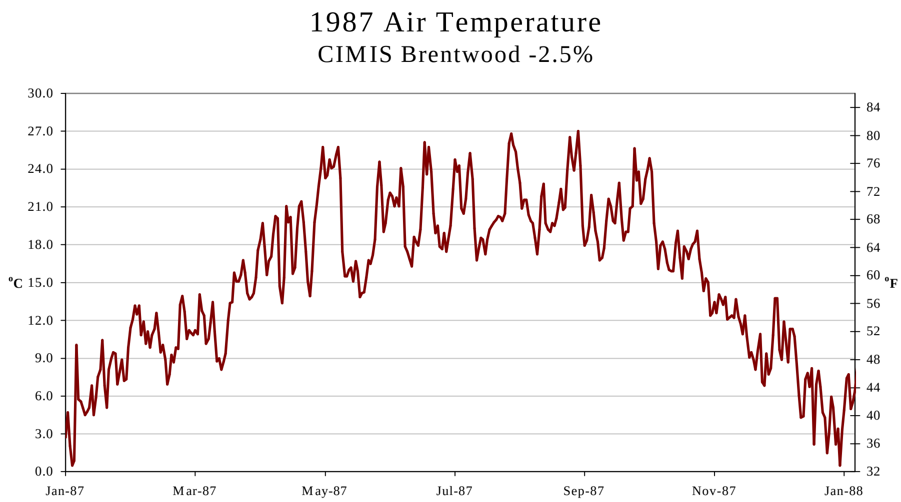


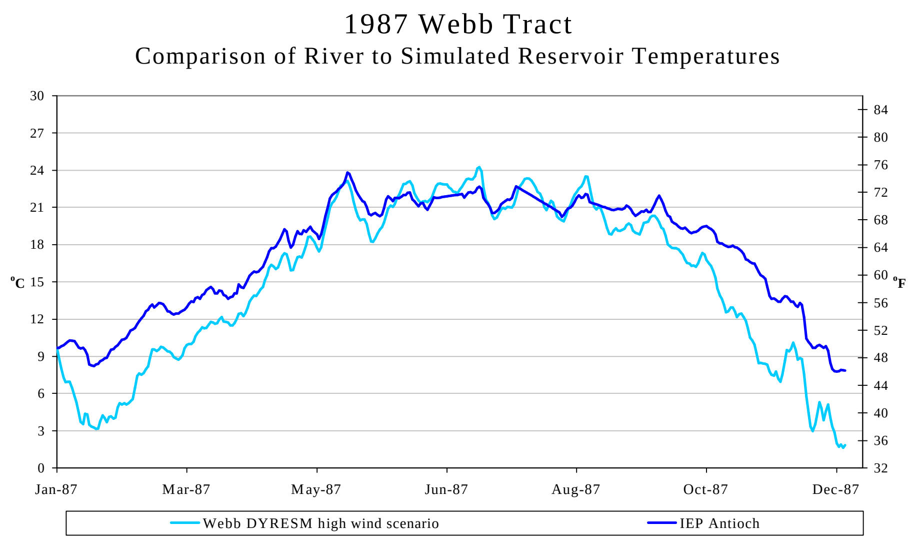


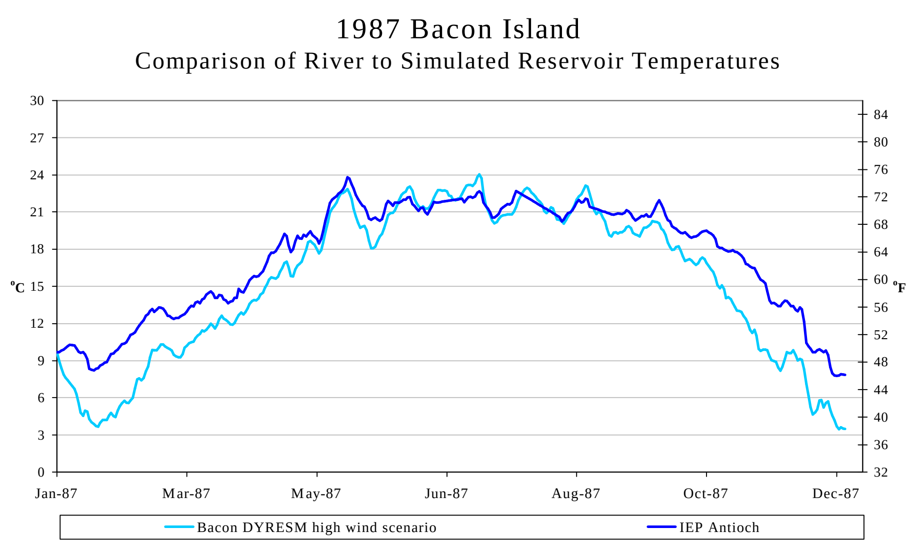
Webb Tract
1987 High Wind (Bin Scaling Approach) DYRESM Profiles



1987 Temperature Data

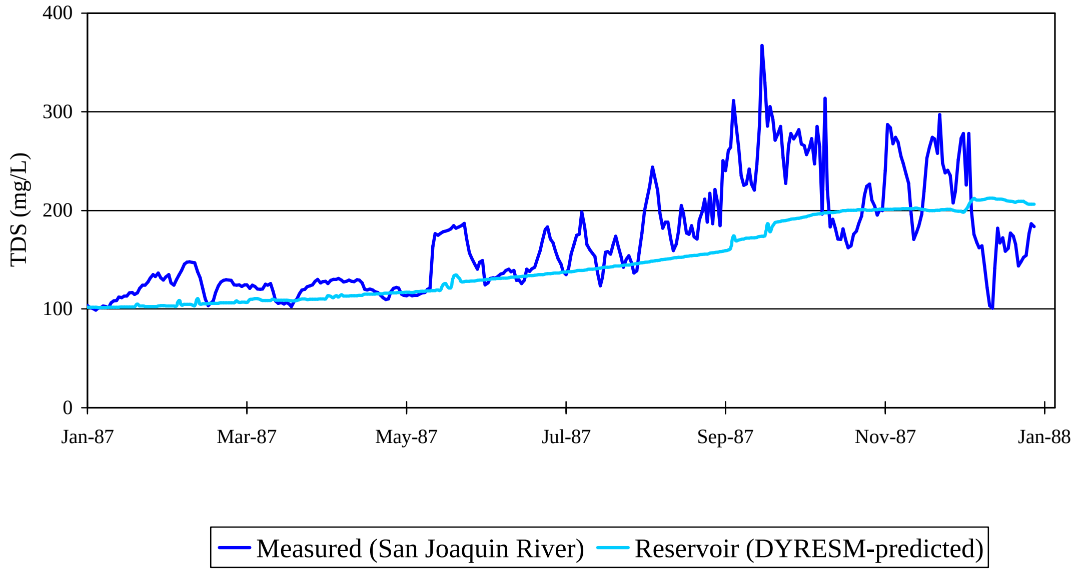




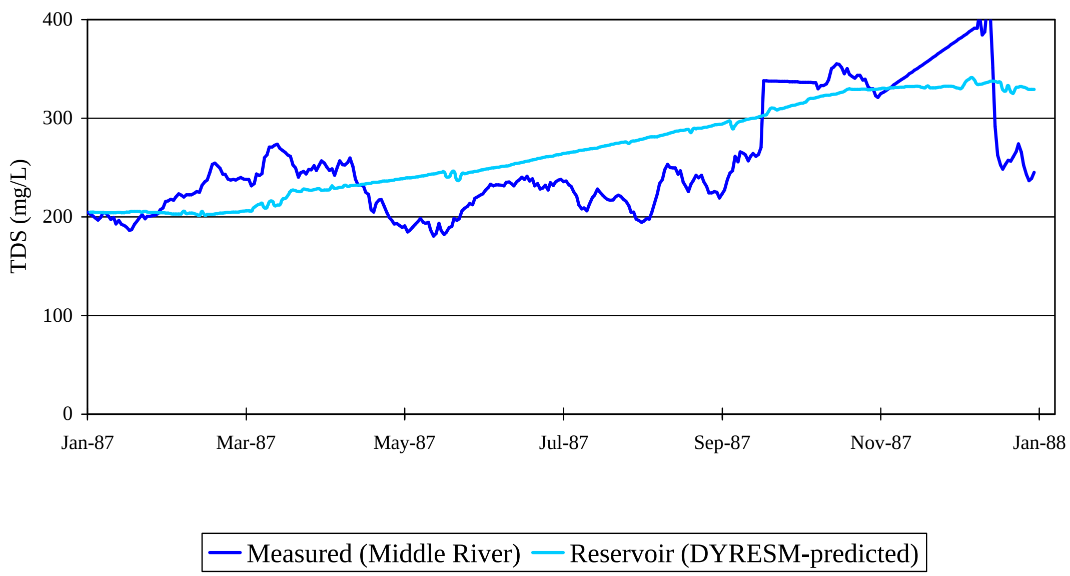


Salinity
1987 River and Reservoir

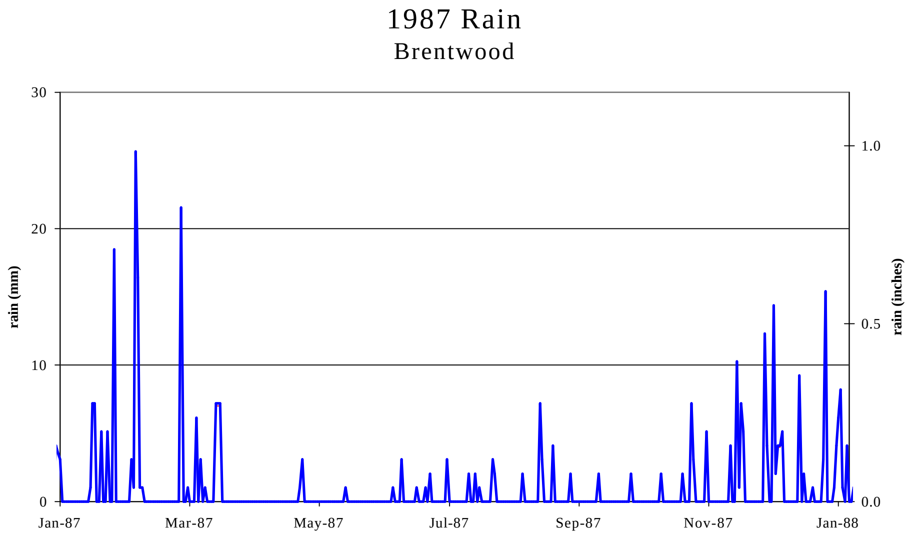
Webb Tract
Daily TDS

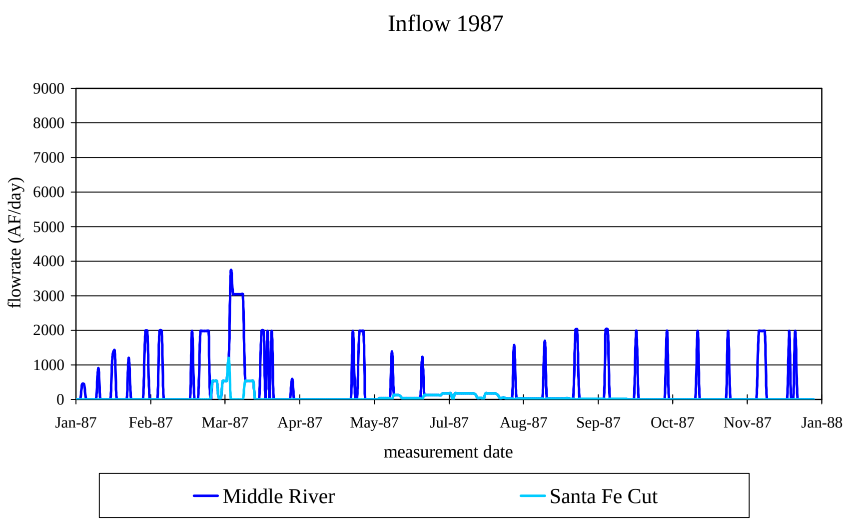


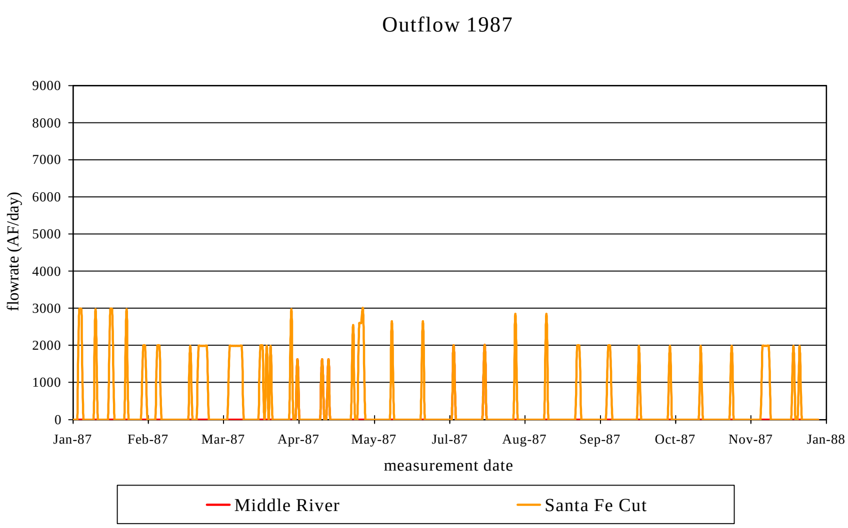
Bacon Island
Daily TDS



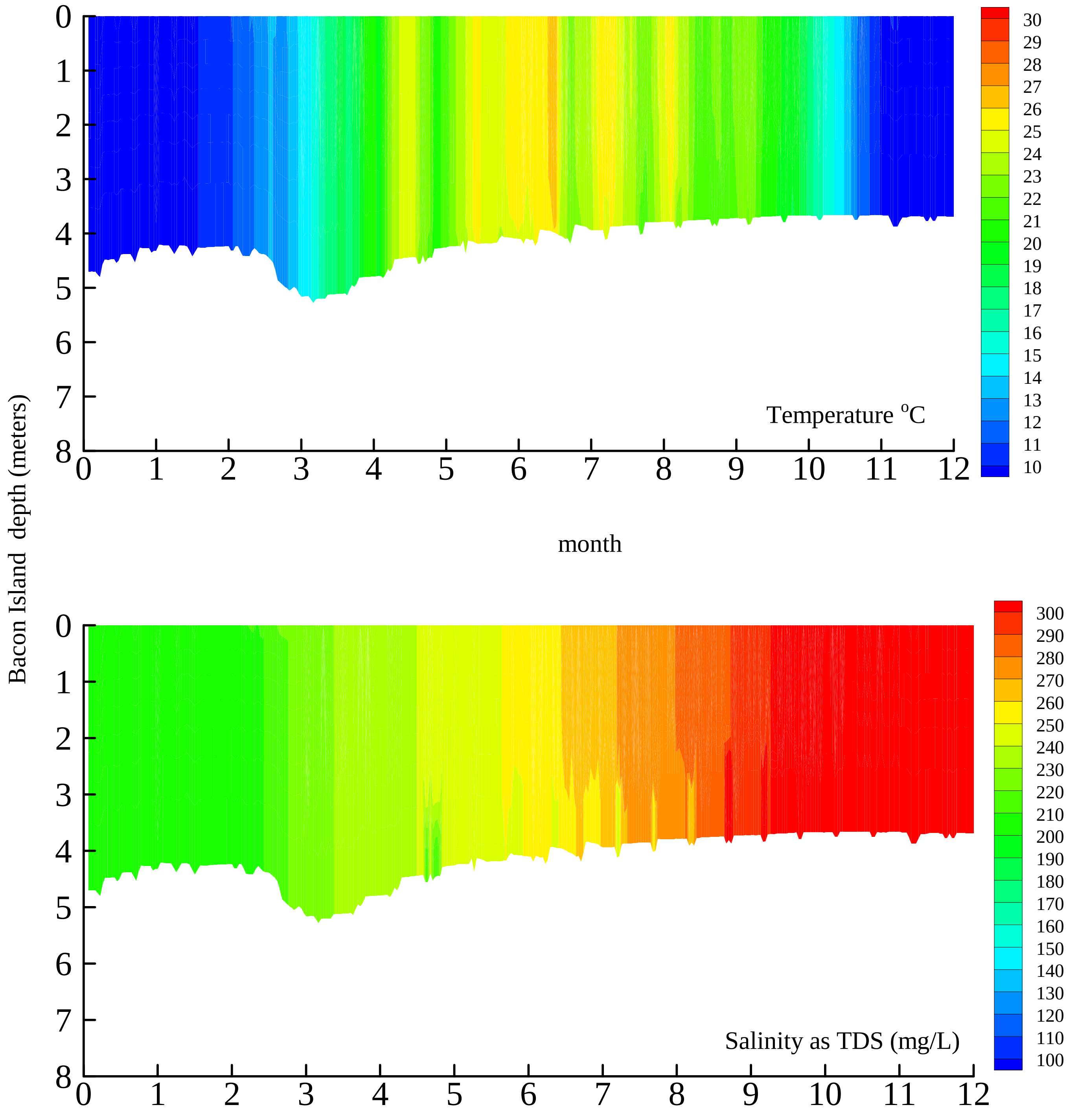
Bacon Island
1987 Flow



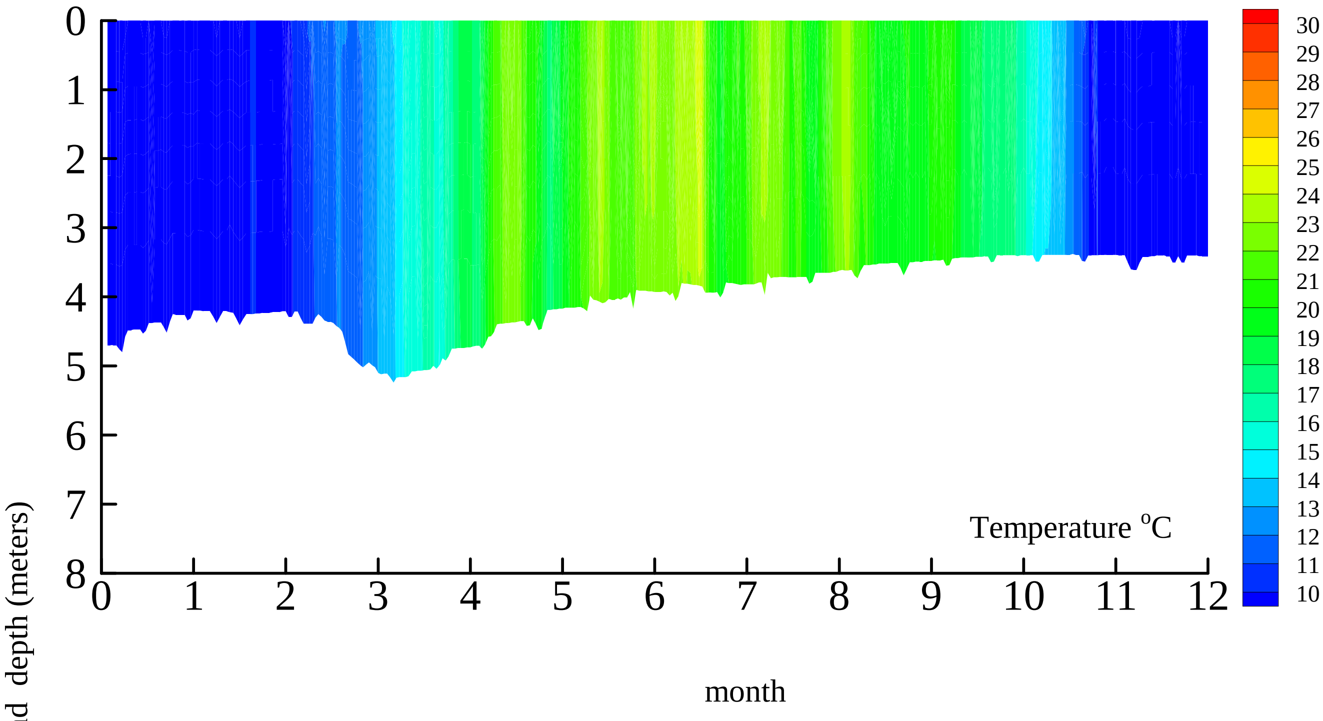


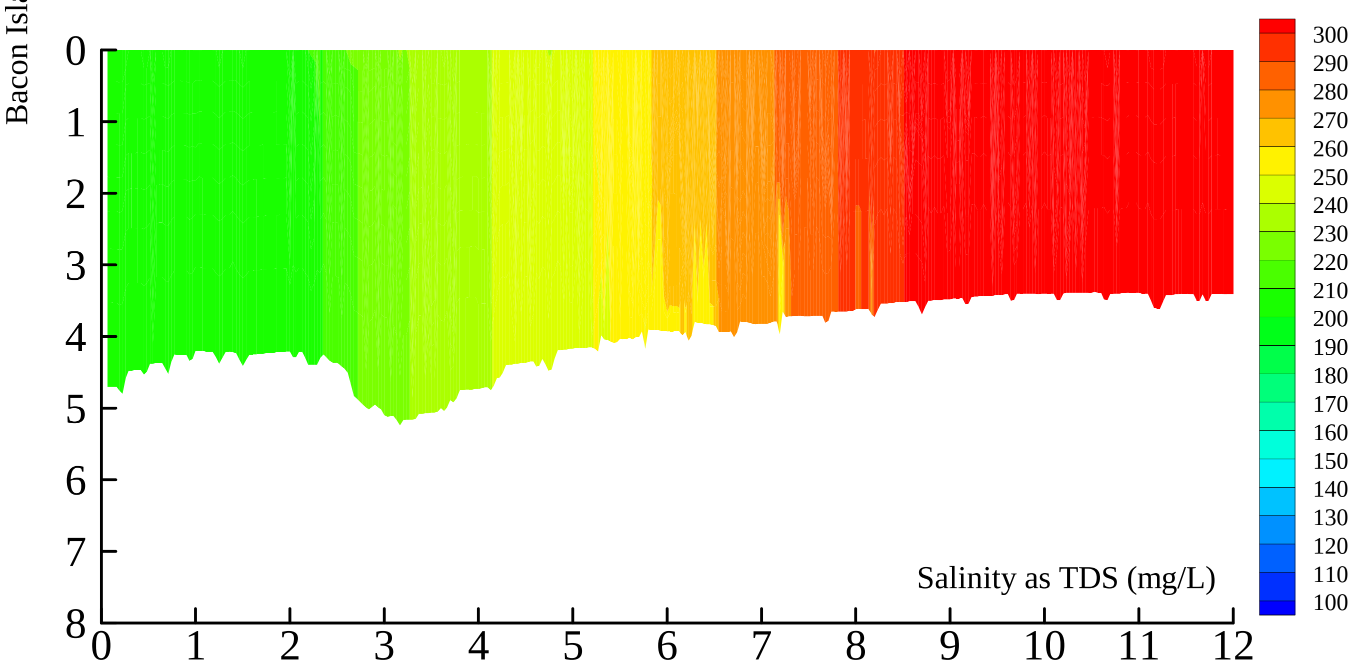


Bacon Island
1987 Low Wind DYRESM Profiles



Bacon Island
1987 High Wind (Uniform Scaling Approach) DYRESM Profiles





Bacon Island
1987 High Wind (Bin Scaling Approach) DYRESM Profiles